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## THESIS

**NUCLEATE POOL BOILING OF R-114/OIL MIXTURES IN A  
SMALL ENHANCED TUBE BUNDLE**

by

**RUSSELL E. HAAS**

**June, 1992**

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**92-30388**



REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School	6b. OFFICE SYMBOL (If applicable) 69	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000		7b. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS		
		Program Element No.	Project No.	Task No.
				Work Unit Accession Number
11. TITLE (Include Security Classification) Nucleate Pool Boiling of R-114/Oil Mixtures in a Small Enhanced Tube Bundle				
12. PERSONAL AUTHOR(S) Haas, Russell Edward				
13a. TYPE OF REPORT Master's Thesis	13b. TIME COVERED From To	14. DATE OF REPORT (year, month, day) 1992 June 17	15. PAGE COUNT 196	
16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
17. COSATI CODES			18. SUBJECT TERMS (continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUBGROUP		
			natural convection and nucleate pool boiling regions, hysteresis loop, oil addition	
19. ABSTRACT (continue on reverse if necessary and identify by block number)				
Heat transfer tests were carried out using a small tube bundle of Turbo-B tubes in a pool of different R-114/oil mixtures. By accurately instrumenting five tubes within the bundle, both the convective and nucleate boiling regions were studied in detail, with emphasis on the 'bundle effect' (ie. the effect of the lower tubes in operation on the upper tubes within the bundle). In addition, the influence of increased amount of oil on the tube bundle was studied to see how this affected the overall heat transfer and in particular, the shape of the hysteresis loop.				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS REPORT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Professor P. J. Marto			22b. TELEPHONE (Include Area code) (408)-646-3382	22c. OFFICE SYMBOL 69 Mx

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**Nucleate Pool Boiling of R-114/Oil Mixtures in a Small Enhanced Tube Bundle**

by

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Submitted in partial fulfillment  
of the requirements for the degree of

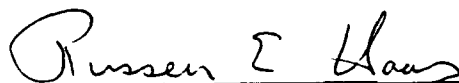
**MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL**

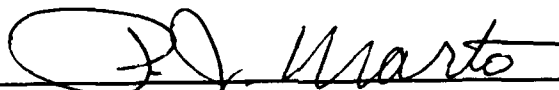
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## ABSTRACT

Heat transfer tests were carried out using a small tube bundle of Turbo-B tubes in a pool of different R-114/oil mixtures. By accurately instrumenting five tubes within the bundle, both the convective and nucleate boiling regions were studied in detail, with emphasis on the 'bundle effect' (ie. the effect of the lower tubes in operation on the upper tubes within the bundle). In addition, the influence of increased amounts of oil on the tube bundle was studied to see how this affected the overall heat transfer and in particular, the shape of the hysteresis loop.

Accession For	
NTIS CRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

DTIC QUALITY INSPECTED 8

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## NOMENCLATURE

<u>SYMBOL</u>	<u>UNITS</u>	<u>NAME/DESCRIPTION</u>
$A_{as}$	V	Voltage output from current sensor
$A_c$	$m^2$	Tube-wall cross sectional area
$A_s$	$m^2$	Area of heated surface
$C_p$	J/kg K	Specific heat
$D_i$	m	Inside tube diameter
$D_o$	m	Outside tube diameter
$D_{tc}$	m	Thermocouple location diameter
fpi		Fins per inch
$g$	$m/s^2$	Gravitational acceleration
$h$	$W/m^2 K$	Heat transfer coefficient of enhanced tube surface
$h_b$	$W/m^2 K$	Heat transfer coefficient of tubes unheated ends
$h_t$	m	Height of liquid column above a instrumented tube
$k$	$W/m K$	Thermal conductivity of refrigerant
$k_{cu}$	$W/m K$	Thermal conductivity of copper
$L$	m	Heated length of the tube
$L_u$	m	Unheated length of the tube
$L_c$	m	Corrected unheated length of the tube
$n$	1/m	Parameter in calculation of $q_f$
$Pr$		Prandtl number
$p$	m	Perimeter of the tube outside surface
$\Delta P$	Pa	Hydrostatic pressure difference between tube and liquid free surface

$q$	W	Heat transfer rate
$q''$	W/m <sup>2</sup>	Heat flux
$q_f$	W	Heat transfer rate from unheated smooth tube ends
$t$	m	Thickness of the tube wall
$T$	C	Temperature
$T_{\text{film}}$	C	$(T_{\text{sat}_c} + \bar{T}_{\text{wo}}) / 2$ , Film temperature
$T_{\text{filmK}}$	K	Film thermodynamic temperature
$T_{\text{ld1}}$	C	Liquid temperature reading from T(3)
$T_{\text{ld2}}$	C	Liquid temperature reading from T(4)
$T_{\text{sat}}$	C	Saturation temperature
$T_{\text{sat}_c}$	C	Corrected saturation temperature due to hydrostatic pressure difference
$\bar{T}_{\text{wi}}$	C	Average inside wall temperature
$\bar{T}_{\text{wi-K}}$	K	Average inside wall thermodynamic temperature
$\bar{T}_{\text{wo}}$	C	Average outside wall temperature
$V_{\text{as}}$	V	Voltage output from voltage sensor
$\alpha$	m <sup>2</sup> /s	Thermal diffusivity
$\beta$	1/K	Thermal expansion coefficient
$\mu$	kg/m s	Dynamic viscosity of liquid
$\nu$	m <sup>2</sup> /s	Kinematic viscosity of liquid
$\rho$	kg/m <sup>3</sup>	Density of liquid
$\Phi$	C	Fourier conduction term
$\theta_b$	C	$\bar{T}_{\text{wo}} - T_{\text{sat}_c}$ , Wall Superheat



## I. INTRODUCTION

### A. BACKGROUND

One of today's major environmental concerns is the depletion of the earth's protective ozone layer. In 1987, an international conference was held in Montreal, Canada to address the problems caused by Chlorofluorocarbons (CFCs) to the earth's ozone layer. CFCs are manmade chemicals of chlorine, fluorine, and carbon and are unique in that they have a combination of desirable properties: low in toxicity, non-flammable, non-corrosive, non-explosive, extremely stable and compatible with many other materials. This extreme stability is what causes problems to the ozone layer due to the fact that CFCs only break down in the upper atmosphere when subjected to intense ultraviolet radiation. This break down produces chlorine which has been linked to the depletion of the earth's ozone layer.

In September 1987, 24 nations representing the United Nations Environment Program (UNEP) met and signed the Montreal Protocol. They discussed the substances that deplete the ozone layer [Ref.1] and called for a near-term freeze on the production and consumption of these substances. The agreement required production of these chemicals to be cut back to 1986 levels followed by a two-phased reduction culminating in cutbacks of 50% by mid-1998; this came into effect on July 1, 1989. In 1990, a progress meeting was held in London where UNEP delegates agreed to completely phase out all CFCs by the year 2000 [Ref. 2]. In the spring of

1992, President Bush pushed up the complete phase out of CFC's by the year 1995.

The U.S. Navy uses a number of different CFCs (designated by "R" for refrigerants) for various refrigeration and air conditioning (AC) needs. Presently, the U.S. Navy has approximately 1850 shipboard AC plants using both R-12 (in reciprocating compressor) and R-114 (in centrifugal compressor) plants. To comply with the Montreal Protocol and U.S. legislation, the Mechanical Systems Branch (Code 2772) at the Naval Surface Warfare Center (NSWC) is pursuing research in the elimination of shipboard use of CFCs. As mentioned by Chilman [Ref. 3] this research is to be completed in three phases:

1. To identify in the short term suitable alternative ozone-safe chemicals to replace R-114 and R-12. To accomplish this task, the heat transfer characteristics must be similar to the existing refrigerants in place and hence the need for a database exists for current refrigerants (R-114 and R-12) so that they can be compared to the new proposed refrigerants (HFC-124 and HFC-134A respectively).

2. In the longer term, to research, develop, and test substitute chemicals and alternative technologies to replace existing CFC uses.

3. To implement new cooling system technologies into the fleet which do not depend on CFCs or their replacement.

This thesis is a continuation of the previous work at NPS and supplements NSWC's research on alternatives to CFCs by establishing baseline nucleate pool boiling data of pure R-114 and R-114/oil mixtures from a small bundle of enhanced tubes representing a section of a flooded evaporator. Emphasis is placed on the natural convection and boiling

regions, hysteresis phenomena, and analysis of various oil concentrations on the overall heat transfer performance.

## **B. OBJECTIVES**

The objectives of this thesis are as follows:

1. Understand in greater detail both the convection and nucleate pool boiling phenomena and hysteresis effects within a small Turbo-B tube bundle.

2. Obtain data using a Turbo-B tube bundle for increasing and decreasing heat flux for R-114/oil mixture with oil concentrations of 0, 1, 2, 3, 6, and 10 percent.

3. Compare data with earlier studies at the Naval Postgraduate School using R-114/oil mixtures for other enhanced tube surfaces.

## II. LITERATURE SURVEY

### A. SMOOTH TUBE BUNDLES

In recent years significant progress has been made in understanding nucleate boiling heat transfer phenomena on the shell side of flooded evaporators. Extensive work on smooth tube bundles has been reported by Cornwell (Leong and Cornwell [Ref. 4], Cornwell et al. [Ref. 5], Cornwell and Scoones [Ref. 6], Cornwell [Ref. 7]). Cornwell and Schuller [Ref. 8] conducted a photographic study of boiling R-113 in a smooth tube bundle at one atmosphere. One of their conclusions was that bubbles leaving the lower tubes in the bundle impacted and caused a sliding motion around the upper tubes. Cornwell and Schuller observed the two-phase flow patterns and deduced that sliding bubbles from lower tubes on upper tubes could account for significant heat transfer in the top part of the bundle. Cornwell [Ref. 7] later found that in the nucleate boiling region, sliding bubbles and liquid forced convection could account for all the heat transfer in the top of the bundle.

The influence of tube position within a bundle of smooth tubes using R-11, R-12, R-22 and R-113 has been studied extensively by Wallner [Ref. 8], Fujita et al. [Ref. 9], Chan and Shourki [Ref. 10], Rebrov et al. [Ref. 11], and Marto and Anderson [Ref. 12]. Using both in-line and staggered tube arrangements with various tube pitch-to-diameter ratios between 1.2 and 2.0, their work verified that the influence of the lower tubes in a bundle can significantly increase the heat transfer performance

of upper tubes at low heat fluxes due to two-phase convective effects. At high heat fluxes (typically  $> 50 \text{ kW/m}^2$ ) in the fully developed nucleate boiling region, the data for all the tubes merged onto a single curve. This is representative of a single smooth tube and shows that there is no 'bundle effect' (ie. no improvement over a single tube under similar conditions) in the high heat flux (nucleate boiling) region.

Chan and Shoukri [Ref. 10] studied the boiling characteristics of a smooth in-line tube bundle in R-113. They concluded that at lower heat fluxes, the heat transfer process is strongly influenced by two-phase convection effects, resulting in higher heat transfer coefficients on the upper tubes. At high heat fluxes, however, they found that the dominant mode of heat transfer was nucleate boiling from the upper tubes and that convective effects from below were insignificant. At these high fluxes, the bundle performance was similar to the trends of a single tube in a single tube apparatus. Fujita et al. [Ref. 9] also found that the heat transfer at low heat fluxes using a smooth tube bundle in R-113 was enhanced by convection induced by rising bubbles (ie. a steady increase in performance of the upper tubes as additional lower tubes were activated). They attributed this enhancement to the "positive bundle effect". At high heat fluxes, this enhancement disappeared.

Anderson [Ref. 13] found similar effects as above for a smooth tube bundle in pure R-114. Furthermore, he reported that the presence of up to 3% oil (by mass) actually improved the heat transfer performance. This is similar to data reported for a single smooth tube by Wanniarachchi et al. [Ref. 14]. Furthermore, at an oil concentration of 10%, only a slight degradation in the heat transfer (compared to pure R-114) was found. He

obtained a maximum heat transfer performance for the bundle at an oil concentration of 2%.

## B. ENHANCED TUBE BUNDLES

Much less work has been done on enhanced tubes (Enhanced means any surface that is not smooth). However, the effects at high and low heat fluxes mentioned above are similar to those obtained for finned tube bundles by Yilmaz and Palen [Ref. 15], Muller [Ref. 16], and Hahne and Muller [Ref. 17]. Stephen and Mitrovic [Ref. 18] looked at R-12 and R-114 boiling from a GEWA-T tube bundle. Apart from the magnitude of the heat transfer coefficient varying with fluid, the trends are very similar to those mentioned above for smooth and finned tube bundles.

For porous coated surfaces, Czikk et al. [Ref. 19] found no 'bundle effect' over a wide range of heat flux ( $1-100 \text{ kW/m}^2$ ) and the bundle data agreed closely with single tube data. Arai et al. [Ref. 20] found that the 'bundle effect' for a Thermoexcel tube bundle was smaller than that found for a smooth or finned tube bundle. However as before, any 'bundle effect' was eliminated at high heat fluxes where the data for all the tubes agreed closely with single Thermoexcel tube results. These effects are similar to those found by Czikk et al. [Ref. 19] for the porous coated.

Chilman [Ref. 3] reported experiments with a Turbo-B tube bundle in pure R-113, conducting both increasing and decreasing heat flux tests. He concluded that in the natural convection region, heated lower tubes do not have any influence on the heat transfer from upper tubes. Also, Chilman

reported the presence of heated lower tubes within a bundle reduced the incipient boiling point.

Stephan and Mitrovic [Ref. 18] reported the influence of oil on the boiling heat-transfer coefficient of R-12 using a T-shaped finned tube (Gewa-T) bundle. They reported that the ratio of oil to no oil heat-transfer coefficients decreased with the mass fraction of oil for all except the highest heat flux ( $22 \text{ kW/m}^2$ ) where an increase in heat transfer was noted for oil concentrations between 1 and 6%. They concluded that the influence of oil on heat transfer was mainly due to the thermal properties of the specific oil used in the experiments and its interaction with the refrigerant.

Schlager et al. [Ref. 21] summarized the influence of oil on refrigerant in pool boiling. They stated that under certain conditions (typically low pressure and high heat flux), the heat transfer coefficient increased at low oil concentration. Stephan [Ref. 22] first pointed this out and attributed the phenomenon to foaming. Burkhardt and Hahne [Ref. 23] for a finned tube bundle found that the maximum heat transfer coefficient, which was 10% to 15% above the oil-free value, occurred at a concentration of about 4%.

Heimbach [Ref. 24] conducted experiments with R-12/oil mixtures on a finned tube bundle. He reported that the presence of up to 2% oil, did not affect the heat transfer performance significantly. However at higher concentrations (3% to 7%), an increase in the heat transfer was observed. He also attributed this to foaming and postulated that changes in the properties of the mixture might facilitate the formation of bubbles.

Anderson [Ref. 13] and Akcasayar [Ref. 25] conducted experiments with finned (19 fpi) and High Flux (porous coated) tube bundles in pure R-114 and R-114/oil mixtures in the same apparatus. Anderson reported a maximum heat transfer performance at an oil concentration of 3% for the finned tube bundle. Akcasayar also reported that the finned tube bundle performance increased 1.65 times with 3% oil concentration (compared with pure R-114) at the maximum heat flux level. For 6% and 10% oil concentrations, the performance of the bundle, when compared with lower oil concentrations, decreased. This was especially significant at a 10% oil concentration. Compared with the finned tube bundle, the High Flux tube bundle had a 1.5 times better heat transfer performance at a heat flux of 30 kW/m<sup>2</sup> in pure R-114. However, these performance ratios decreased with increased oil concentrations such that the finned bundle outperformed the High Flux bundle at 6% oil concentration. This was especially true at the highest heat fluxes where the High Flux bundle performance was not much better than a smooth tube bundle of similar size.



### III. EXPERIMENTAL APPARATUS

#### A. TEST APPARATUS OVERVIEW

The experimental apparatus including the auxiliary equipment and the evaporator/condenser is shown in Figure 1. The following is only a general description of the whole experimental apparatus. A more detailed look at the condenser and evaporator is provided in section C. Further information about the apparatus is provided by Murphy [Ref. 26] and Anderson [Ref. 13].

The experimental apparatus is essentially made up of three closed loops. The first loop consists of an 8 ton refrigeration unit located outside the laboratory which is used to cool an ethylene glycol/water mixture. The second loop is the ethylene glycol/water mixture flowing through the condenser. This mixture is contained within a large sump within the laboratory. The flow rate through the condenser is delivered by two pumps which can be operated independently or together; this coolant mixture condenses the refrigerant vapor in the condenser and maintains system pressure and temperature. Pump number one provides coolant flow through the four test condenser tubes as well as to one of the auxiliary condenser coils (bottom coil). Pump number two provides coolant through a manifold which distributes the coolant to the remaining four auxiliary condenser coils within the condenser. The third loop is the evaporator and condenser itself designed for reflux operation. The vapor generated

in the evaporator flows upward and condenses in the condenser; the condensate then returns to the evaporator via gravity.

## **B. AUXILIARY EQUIPMENT**

### **1. 28 kW Refrigeration Unit**

This unit was used to cool a 1.8 m<sup>3</sup> reservoir sump of an ethylene glycol/water mixture (coolant) to the desired temperature needed to condense the refrigerant vapor. For R-114, the temperature control was set to maintain the sump at -15 °C. The refrigeration unit had a cooling capacity of 28 kW (8 tons).

### **2. Ethylene Glycol/Water Mixture**

The coolant used was a 54% (by weight) ethylene glycol/water mixture. This refrigerated mixture was used to control the system pressure and temperature by circulating coolant through the auxiliary condenser coils and/or condenser test tubes at different flow rates.

### **3. Pumps**

Two pumps were available to circulate the coolant from the sump through the condenser. Pump number one fed four test condenser tubes and one of the auxiliary condenser coils. Pump number two fed the other four auxiliary condenser coils. Pump number one was the primary pump used at low heat fluxes; pump number two was started (as necessary) at high heat fluxes to maintain the desired saturation pressure in the evaporator.

### **4. Flowmeters**

Five calibrated float-type flowmeters, connected to pump number one, were used to measure the flow rates passing through the four test condenser tubes and one auxiliary condenser coil. One additional

flowmeter (connected to pump number two) was used to measure the total flow to the remaining four auxiliary condenser coils. Each of the five auxiliary condenser coils had a globe valve to regulate (or shut off) flow as desired. For the four test condenser tubes, the coolant flow was regulated by a flowmeter valve.

### C. EVAPORATOR/CONDENSER

An overall view of the evaporator and condenser is shown in Figure 2. The evaporator was designed to simulate a small portion of a refrigerant flooded evaporator. Front and side views of the evaporator are shown in Figures 3 and 4. It was fabricated from stainless steel plate and formed into a short cylinder, 610 mm in diameter and 241 mm long. Electrically-heated tubes were cantilever-mounted from the back wall of the evaporator to permit viewing along the axis of the tubes through the lower of two viewing windows. A plexiglas plate was attached to the front of the tube bundle to ensure tube alignment during experiments. Each viewing window had a layer of glass and plexiglas, the glass being used on the refrigerant side in order to prevent surface cracking of the plexiglas. The plexiglas gave the glass added strength and served as a safety barrier in case the glass broke during pressurization.

The electric power can be applied separately to each set of heaters using a STACO 240 V, 23.5 kVA rheostat controller shown in Figure 5. Also, the desired number of instrumented tubes, active tubes, simulation or auxiliary heaters can be individually activated by using circuit breakers. The five simulation heaters, each with a maximum rating of 4 kW, were mounted below the test bundle in order to simulate 15 additional

tube rows in a larger bundle and to provide an inlet vapor quality into the bottom of the test bundle as suggested by Webb [Ref. 27]. The liquid pool was maintained at 2.2 °C (corresponding to a saturation pressure of 1 atmosphere) by passing coolant through the condenser.

Figure 6 is a schematic sectional view of the evaporator that shows the four kinds of heated tubes installed in the evaporator. These were instrumented, active, auxiliary, and simulation. For this study only the instrumented, active, and simulation heaters were used; the auxiliary heaters are needed for experiments either at higher pressures or for other refrigerants which have a higher normal boiling point (such as R-113). Table 1 gives the power rating for these heaters and the number used in the evaporator.

The tube bundle itself consists of instrumented, active, and dummy tubes. The location of each tube is represented by the respective letter I, A, and D as shown in Figure 6. The test bundle consists of two types of heated tubes: 12 active tubes (marked "A") which contained 1 kW cartridge heaters, and 5 instrumented tubes (marked "I") which, in addition to the 1 kW cartridge heaters, contained six wall thermocouples each.

In measuring boiling heat transfer coefficients, great care must be exercised with the cartridge heater and temperature measuring instrumentation to ensure good accuracy. The instrumented test tubes were fabricated using the same method as that used by Hahne and Muller [Ref. 17] and Wanniarachchi et al. [Ref. 14]. The exact procedure can be found in Eraydin [Ref. 28]. Figure 7 is a cross-sectional sketch of an instrumented tube, showing the construction details and the location of the wall thermocouples. The thermocouples were embedded in the wall at

different circumferential and longitudinal positions along the heated section of the tube shown in Figure 7.

The five instrumented tubes were located along the centerline of the tube bundle, forming a vertical in-line column. All the instrumented and active tubes were Turbo-B tubes made by Wolverine Tube Co. (see Section E). These tubes were nominally 15.9 mm in outside diameter and were arranged in an equilateral triangular pitch (ie. centerline-to-centerline spacing) of 19.1 mm, giving a pitch-to-diameter ratio of 1.35. The thickness of the Turbo-B enhancement was 0.85 mm giving a diameter to the base of the enhancement of 14.2 mm.

The bundle also contained a number of unheated dummy smooth tubes (marked "D") that were used to guide the two phase mixture through the bundle. The dummy tubes were made from commercially available 15.9 mm OD smooth copper tubing. Two vertical baffle plates made of aluminum were used on either side of the bundle to restrict circulation into and out of the bundle at the sides. A dummy rack (Figure 8) consisting of 12 solid rods made of aluminum (15.9 mm OD and spaced 19.1 mm from centerline-to-centerline) was placed below the tube bundle. This rack had a triangular pitch arrangement with vapor retaining plates on the sides and was designed for two purposes: to collect all rising two phase flow generated by the simulation heaters and direct it into the test bundle and to simulate vapor passing through a large bundle before reaching the instrumented tubes. A small open space (approximately 5 mm in height) was left between the bundle and dummy tube rack. This space allowed some refrigerant from below to enter the bundle and replace the vapor being generated in the bundle. However, there was also a space below the dummy

rack that allowed the majority of the circulation to occur. Thus, liquid/vapor circulation was vertically upward over the five instrumented test tubes with no net horizontal component. Most of the liquid-vapor mixture after passing through the bundle was separated when it reached the pool surface. However, due to the strong circulation patterns set up within the liquid pool, some vapor bubbles remained trapped in the liquid and circulated around the pool.

The condenser included four test tubes (each 1.219 m in length and 15.9 mm OD) in a vertical in-line column and five auxiliary copper coils. For the boiling experiments, these tubes were used to regulate the pressure and temperature in the evaporator. The condenser was designed to permit independent condensation studies of small in-line tube bundles, using the evaporator as a source of vapor. Details of the condenser can be found in Mazzone [Ref. 29].

#### D. DATA ACQUISITION SYSTEM/INSTRUMENTATION

As described by Akcasayar [Ref. 25], a Hewlett Packard HP-3497A Data Acquisition System, HP-9125 computer and HP-701 printer were used for data acquisition, data reduction and data printing respectively. Although an HP-9826 computer and HP-7470A plotter can be used for final graph printing, a Macintosh computer (using Cricketgraph) was utilized. As described by Anderson [Ref. 13], type-T copper-constantan thermocouples were used to make temperature measurements on the HP-3497A using a relay multiplexer assembly equipped with thermocouple compensation. A 20-channel relay multiplexer card was used to measure the voltage output from both the voltage and current sensors. The voltage measurements were taken

from separate sensors that measured the voltage going to the tube bundle, the simulation heaters and the auxiliary heaters. The total current going through the auxiliary and simulation heaters was measured using an American Aerospace Control (ACC) current sensor. The current to each instrumented tube heater was measured using five identical current sensors. The voltage supplied to the other active tubes was also measured, but the current of each active tube was not. Instead, the total current for a pair of active tubes was measured, and this was sufficient since these tubes each had the same power output (1000 W) as the instrumented test tube heaters and there was no apparent reason to monitor each active tube individually. Computer channel assignments for data acquisition and array assignments are given in Table 2.

#### E. GEOMETRY OF TURBO-B TUBE

The Turbo-B tube, manufactured by Wolverine Tube Inc., contained an enhanced surface geometry. The exterior boiling enhancement is made by raising low integral fins, cutting diagonally across these fins, and then rolling the fins to compress them to form mushroom-like pedestals [Ref. 30]. This process forms numerous re-entrant passageways. Figure 9 shows the surface of the tube at 25 times its actual size. The tube is currently available in copper, cupro-nickel, and low carbon steel.

The relative dimensions of the tube used in this study are as follows:

Tube material - Copper

Nominal Outside diameter - 15.9 mm

Enhanced surface length - 203.2 mm

Thickness of Enhancement - 0.85 mm

Diameter to Base of Enhancement - 14.2 mm





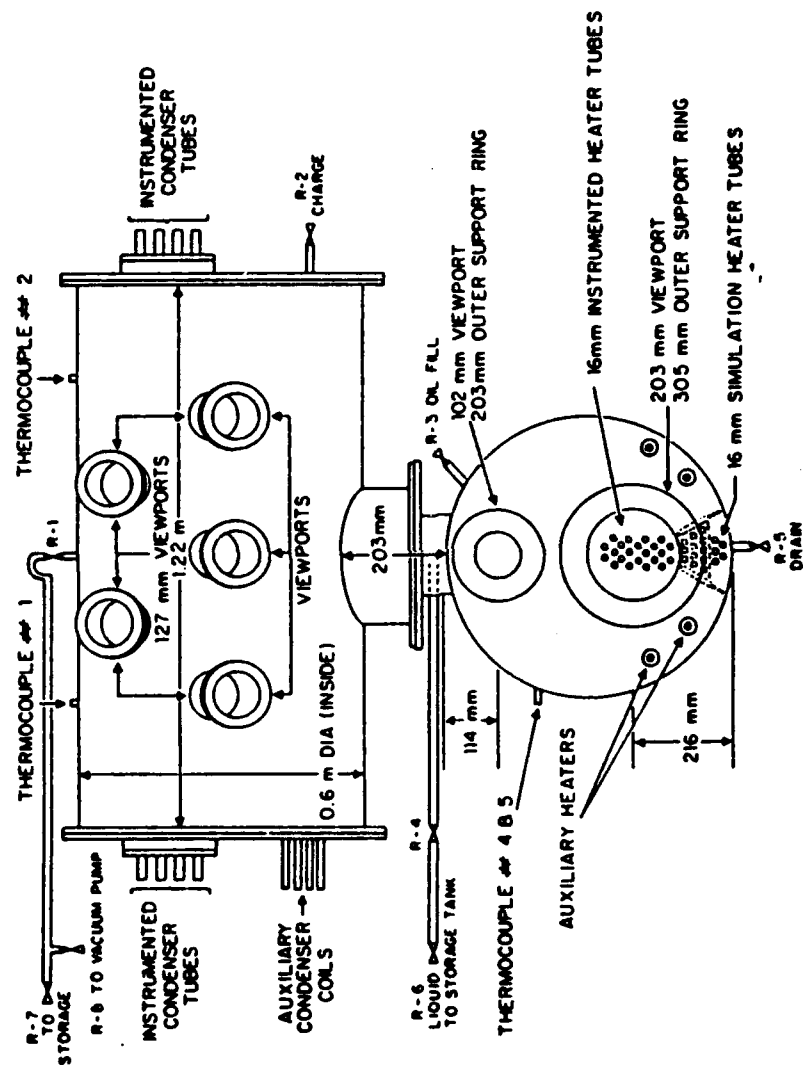


Figure 2. Evaporator/Condenser Schematic

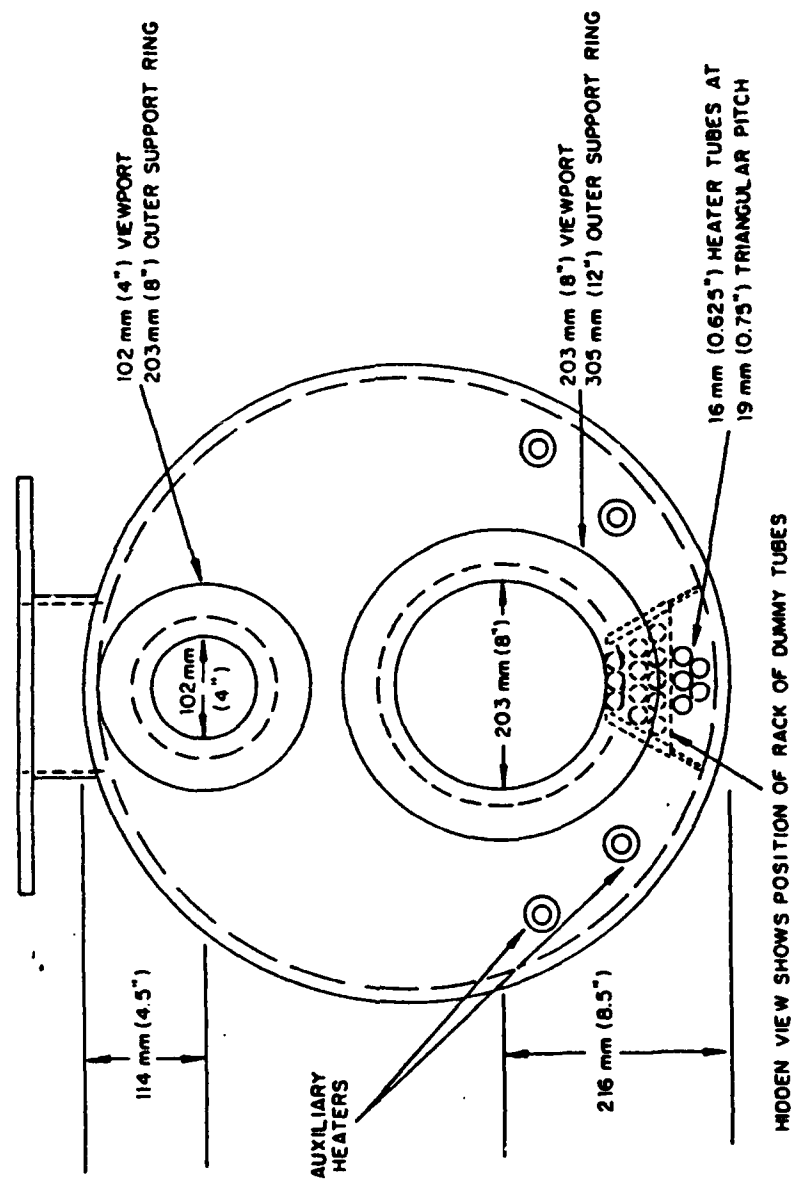


Figure 3. Front View of Evaporator

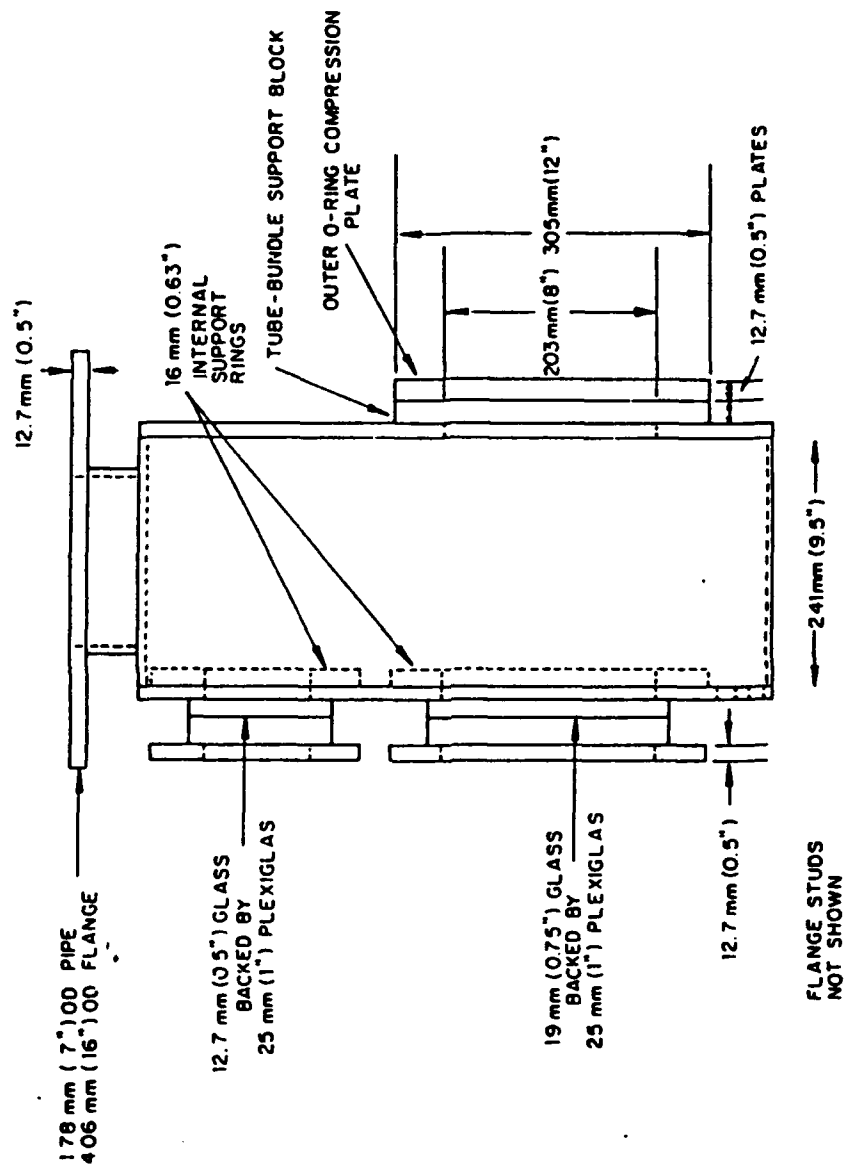


Figure 4. Side View of Evaporator

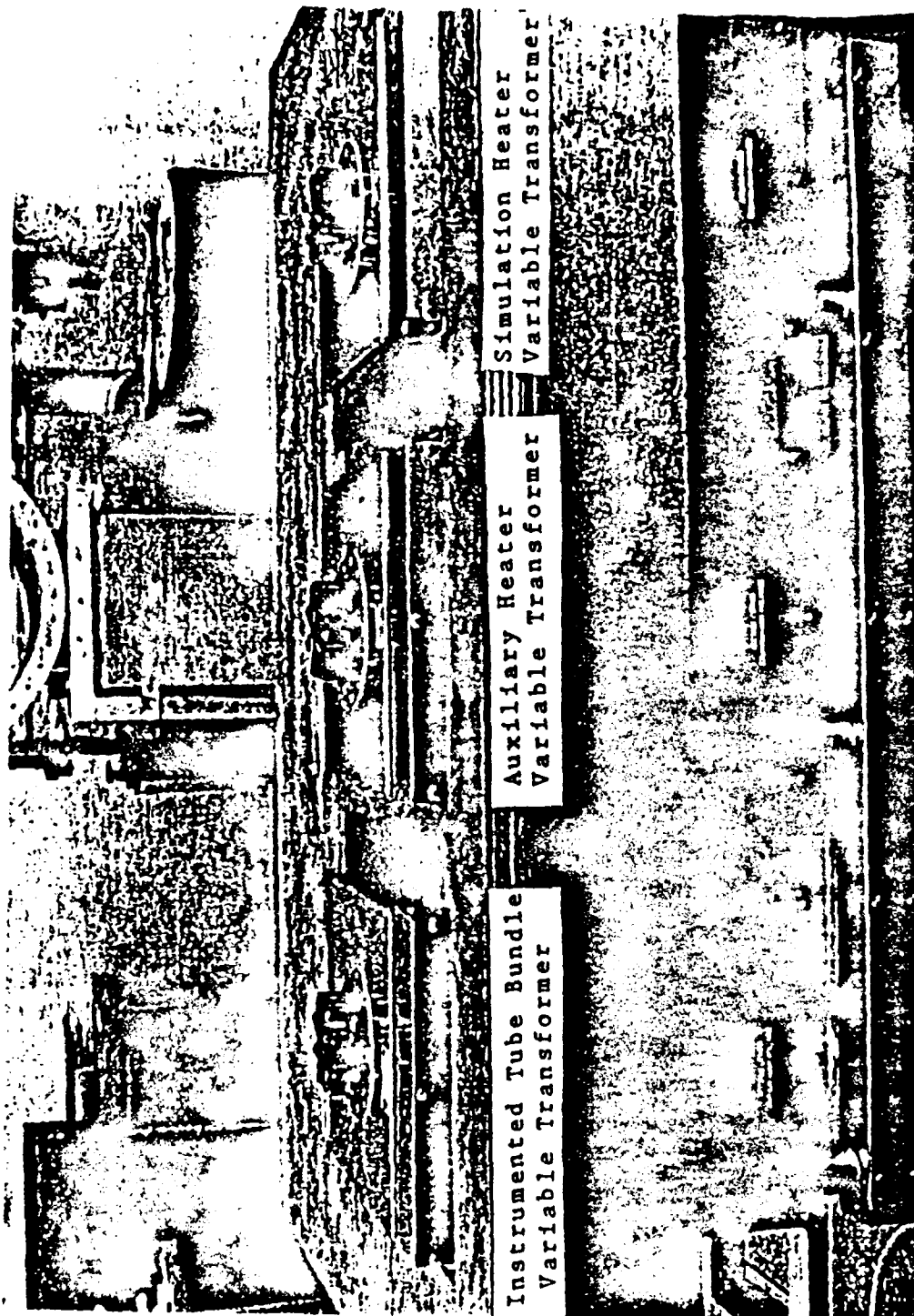


Figure 5. Photograph of 208 V, 75 A, Variable Transformers



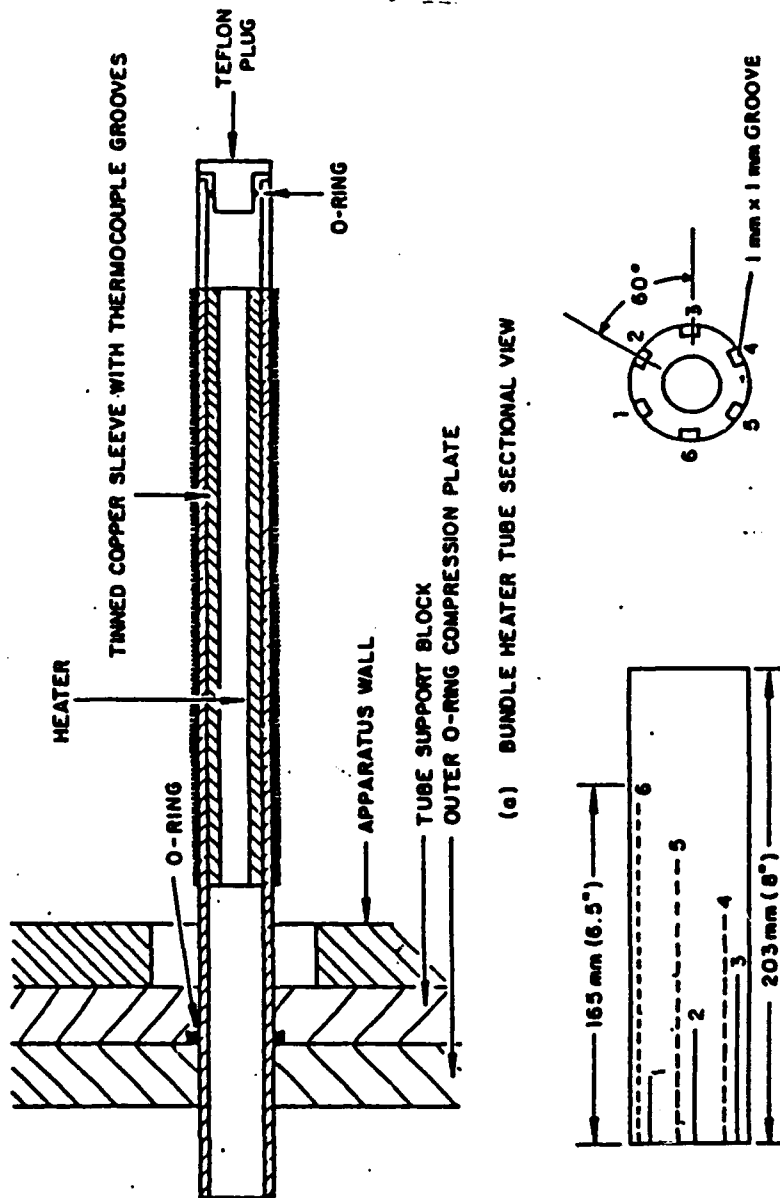


Figure 7. Thermocouple Locations on an Instrumented Boiling Tube and Tube Section View

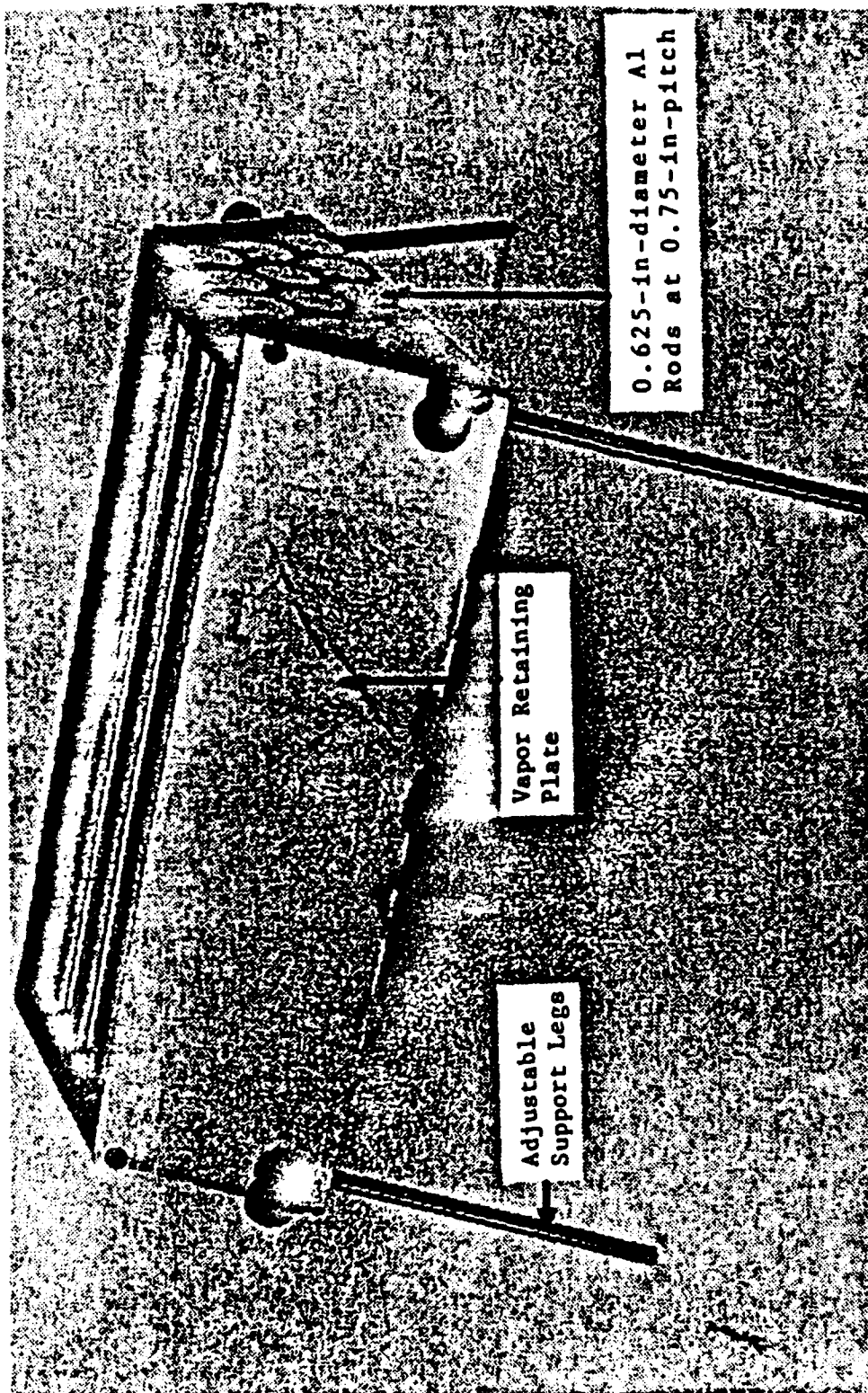


Figure 8. Photograph of Dummy Rack



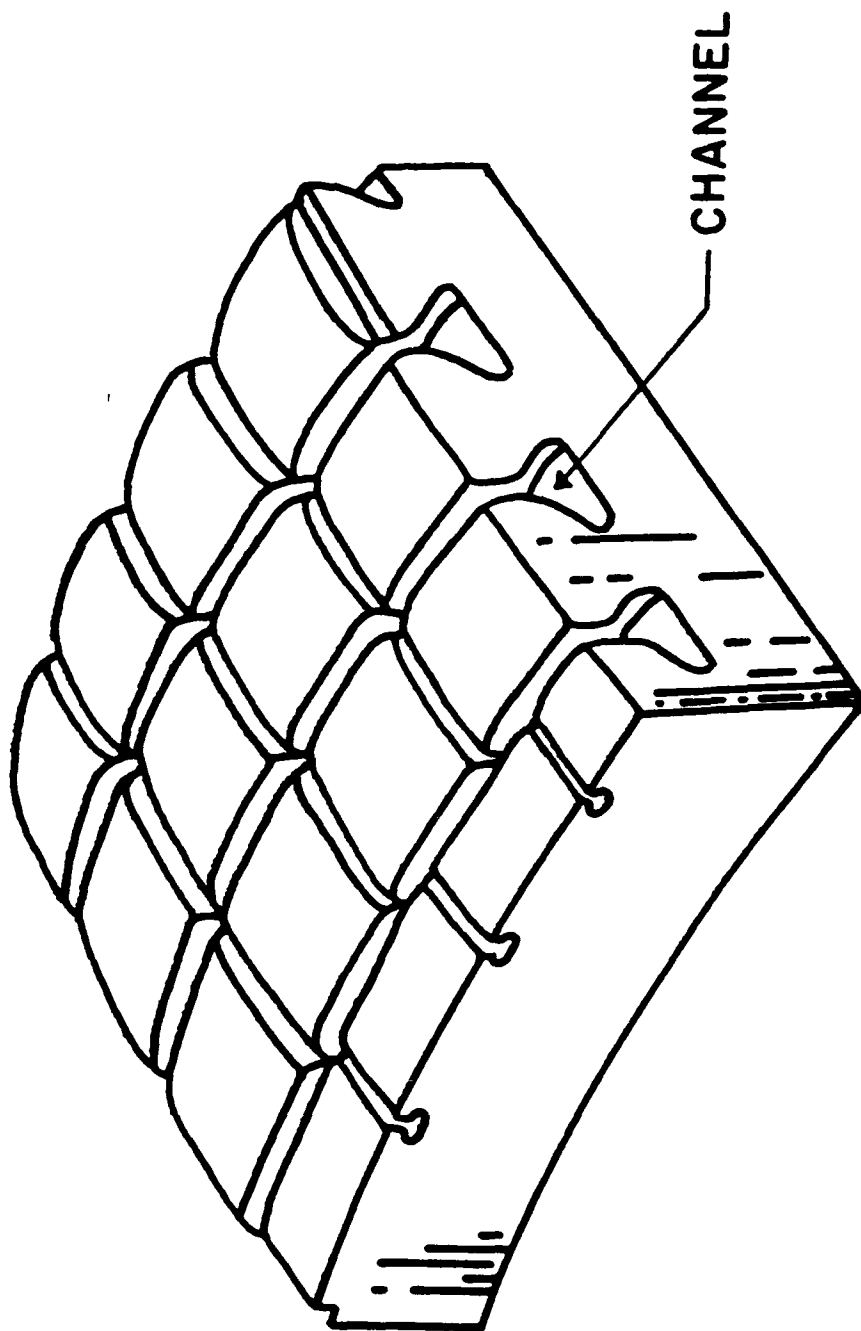


Figure 9. Close-up View of Turbo-B Tube Surface (25 X)

**Table 1. EVAPORATOR HEATERS**

Heater Type	Number	Power Rating per Heater
Instrumented Tube Heaters	5	1000W
Active Tube Heaters	12	1000W
Auxiliary Heaters	4	4000W
Simulation Heaters	5	4000W

**Table 2. COMPUTER/DATA ACQUISITION ASSIGNMENT**

Amperage Sensor Description	Channel	Array
Tube 1	30	Amp(0)
Tube 2	31	Amp(1)
Tube 3	32	Amp(2)
Tube 4	33	Amp(3)
Tube 5	34	Amp(4)
Active Heater Group 1	35	Amp(5)
Active Heater Group 2	36	Amp(6)
Active Heater Group 3	37	Amp(7)
Active Heater Group 4	38	Amp(8)
Active Heater Group 5	39	Amp(9)
Auxiliary Heaters	25	Amp(10)
Simulation Heaters	26	Amp(11)

Voltage Sensor Description	Channel	Array
Instrumented/Active	27	Volt(0)
Simulation Heaters	28	Volt(1)
Auxiliary Heaters	29	Volt(2)

Table 2. COMPUTER/DATA ACQUISITION ASSIGNMENT (CONT.)(cont.)

Thermocouple Description	Channel	Array in code
Vapor 1-Top of Condenser	00	T(0)
Vapor 2-Top of Condenser	01	T(1)
Vapor 3-Top of Evaporator	02	T(2)
Liquid 1-Top of bundle	03	T(3)
Liquid 2-Top of bundle	04	T(4)
Liquid 3-Bottom of bundle	05	T(5)
Tube 1,No. 1	40	T(6)
Tube 1,No. 2	41	T(7)
Tube 1,No. 3	42	T(8)
Tube 1,No. 4	43	T(9)
Tube 1,No. 5	44	T(10)
Tube 1,No. 6	45	T(11)
Tube 2,No. 1	46	T(12)
Tube 2,No. 2	47	T(13)
Tube 2,No. 3	48	T(14)
Tube 2,No. 4	49	T(15)
Tube 2,No. 5	50	T(16)
Tube 2,No. 6	51	T(17)
Tube 3,No. 1	52	T(18)
Tube 3,No. 2	53	T(19)
Tube 3,No. 3	54	T(20)
Tube 3,No. 4	55	T(21)
Tube 3,No. 5	56	T(22)
Tube 3,No. 6	57	T(23)
Tube 4,No. 1	58	T(24)
Tube 4,No. 2	59	T(25)
Tube 4,No. 3	60	T(26)
Tube 4,No. 4	61	T(27)
Tube 4,No. 5	62	T(28)
Tube 4,No. 6	63	T(29)
Tube 5,No. 1	64	T(30)
Tube 5,No. 2	65	T(31)
Tube 5,No. 3	66	T(32)
Tube 5,No. 4	67	T(33)
Tube 5,No. 5	68	T(34)
Tube 5,No. 6	69	T(35)

#### IV. EXPERIMENTAL PROCEDURES

##### A. REMOVAL OF THE TUBE BUNDLE AND BUNDLE DISASSEMBLY

Before starting the removal of the tube bundle from the evaporator, the front glass viewing windows were carefully removed. Next, all thermocouple wires and tube heater electrical connections were disconnected. After this was completed, the nuts securing the backing plate and support block were removed, and the tube bundle was taken out from the back of the evaporator.

When the bundle needed to be disassembled, it was ensured that there was a clean working surface. The first task was to remove the plexiglas plate attached to one end of the aluminum baffle plates (ie. the front of the bundle assembly) by four screws. The ten screws on the side of each aluminum baffle plate were then removed (these were attached to the dummy tubes down each side of the bundle). The aluminum plates were then pulled off the bundle. The four corner dummy tubes (two top and two bottom) remained attached to the tube bundle support block as they were countersunk into the block. The six outer smooth tubes (three per side) could be easily pulled from the aluminum plates as they were attached only by the screws already removed. The other ten smooth tubes were then unscrewed from the tube bundle support block as seen in Figure 10. The smooth tubes were engraved to ensure proper identification during reassembly. With these tubes and aluminum baffle plates removed, only the instrumented and active enhanced heater tubes remained. These tubes were

removed from the support block by loosening the outer O-ring compression plate, disconnecting the active heater tube wired pairs, and pulling the tubes from the block. Reassembly of the tube bundle is done by reversal of this procedure.

#### **B. SYSTEM CLEAN-UP**

If the system had been previously operated with refrigeration oil (or contaminated from some other source) it had to be thoroughly cleaned. To accomplish this, the entire apparatus had to be taken apart and cleaned in the following manner.

After removal of the refrigerant (R-113 by directly draining into 5 gallon drums via drain valve R-5 (see Figure 2 in Chapter 3) at the bottom of the evaporator or R-114 by boiling off into the storage tank by opening R-1 and R-7) and with the system at atmospheric pressure, all electrical connections to the bundle were disconnected and the front viewing glass windows were removed. An electric fan was used for safety to ensure proper ventilation. The tube bundle was then removed and disassembled as described in section A; the dummy tube rack was also removed.

Having removed the tubes from the tube bundle, they were individually washed with warm water, rinsed and then wiped down with acetone. The smooth tubes were cleaned with Copper Brite (a commercial copper cleaning product) to remove any oxidation. They were also wiped down with warm water and then with acetone. The same procedure was followed for the Turbo-B tubes except they were not cleaned with Copper Brite for fear of clogging the channels. During the cleaning process, a soft bristled toothbrush was used to ensure the enhanced surface was cleaned properly,

exercising care not to interfere with the tube surface. The evaporator shell was cleaned in a similar manner, using warm water and acetone.

#### C. INSTALLATION OF THE TUBE BUNDLE

Once the tube bundle had been cleaned and reassembled (see section A), and before tightening the backing plate nuts, the whole assembly was carefully guided back into the evaporator section, ensuring the plexiglas viewing cover of the tube bundle was not damaged. After the bundle was in position, it was ensured that the dummy tube rack was properly positioned below the bundle and that the vapor thermocouple positions were still 1.75 cm above the bundle. Then, all the nuts were tightened equally on opposite sides to give equal compression on the gasket. To replace the front window, very small, equal torques (using a torque wrench) were applied circumferentially to each nut on the outer ring support in turn. After the window was in place, each tube (which extended through the outer O-ring compression plate) was lightly tapped forward so as to touch the front-viewing window. The backing plate was then tightened and the individual tube O-rings compressed, providing a good seal for the system. The compression plate had grooves for the tube O-rings to sit in to help with proper alignment and ensure a good seal.

#### D. SYSTEM LEAKAGE TEST

After the system was isolated from the atmosphere and system integrity was restored, a Seargent Welch 10 SCFM vacuum pump was connected to the apparatus (via valves R-1 and R-8) and the pressure taken down to 25 inHg vacuum. Valves R-1 and R-8 were then secured and the system was left

untouched for at least 24 hours to see if there was any air leakage in. If there was significant leakage ( $>1$  inHg over 24 hours), then the vacuum was broken by cracking open valve R-2 slowly (this ensured that no moisture entered the system). The system was pressurized (with air) to 15 psig through valve R-2. Large leaks could then be detected by simply listening to the air issuing from the system; small leaks were detected by spraying a soapy water solution to all surfaces where leaks were most likely to occur (front viewing glass gaskets, backing plate gasket, all fittings/valves coming off the condenser/evaporator, O-ring seals of the bundle tubes etc). Extreme care must be taken to ensure no moisture enters the inside of the heated tubes where the heater wires protrude. After all leaks were detected and corrected, the system was again subjected to a vacuum for another 24 hour period. If the vacuum held, then the system was ready to receive refrigerant. If not, the above leak correction test was repeated.

#### E. REFRIGERANT

##### 1. Fill

##### a. *From System Storage Tank*

A refrigerant storage tank was used to store R-114 during modification/repairs to the system. The storage tank prevented discharge of the R-114 into the atmosphere and made the experimentation less costly. To fill the evaporator with R-114 from the storage tank, the ethylene glycol/water coolant temperature was first reduced to  $-15^{\circ}\text{C}$ . The system pressure was then maintained below the storage tank pressure (vapor pressure of R-114 at  $20^{\circ}\text{C}$  is approximately 15 psig) by circulation of the

coolant through the condenser test tubes and auxiliary coils. Valves R-6 and R-4 were then opened to draw the R-114 from the storage tank to the evaporator. The amount of refrigerant that was transferred was controlled by throttling valve R-6 to obtain the desired level in the evaporator. If required, additional R-114 could be transferred from a 68 kg storage cylinder to the system using valve R-2 (see section 1.b).

***b. From Refrigerant Storage Cylinder***

To fill the apparatus from the 68 kg storage cylinder, the system pressure was reduced in the same way as above. A hose assembly containing a Drierite gas purifier was connected between the storage cylinder and valve R-2. A gas purifier was used not only to remove all impurities, but also to remove any water from the refrigerant. Once in place, both the storage cylinder valve and R-2 were opened until the desired refrigerant level was reached in the evaporator.

**2. Removal to the Storage Tank**

For tube replacement, system maintenance or system clean up, the R-114 was transferred to the storage tank. The ethylene glycol/water coolant temperature flowing through the storage tank was cooled to  $-15^{\circ}\text{C}$ ; valves R-7 and R-8 were opened and the vacuum pump was turned on to put the storage tank under vacuum. Once the storage tank was under a 20 inHg vacuum, valve R-8 was shut and valve R-1 was opened. Next R-114 was slowly boiled off to the storage tank by using the tube bundle, simulation and auxiliary heaters at a heat flux of  $600\text{ kW/m}^2$  (slow boiling is important to ensure minimum transfer of oil). As the refrigerant level decreased, individual heaters were turned off to ensure none were uncovered. Once



below the level of the heaters, the final few cm of R-114 was boiled off using heat from the atmosphere. Once all of the R-114 was transferred, valves R-1 and R-7 were shut.

#### F. OPERATION

##### 1. System Startup, Securing and Emergency Procedures

See Appendix D

##### 2. Normal Operation

The evaporator was filled with R-114 to a level of approximately 10 cm above the top tubes in the bundle. Prior to operating the system, the 8 ton refrigeration unit was run for approximately an hour to reduce the ethylene glycol/water coolant in the sump to a temperature of  $-15^{\circ}\text{C}$ . The pressure in the evaporator/condenser was usually 12 to 15 psig if the system had been secured overnight. As the sump was brought to temperature, the data acquisition system and computer were turned on. This allowed the temperature in the system to be monitored during cool-down to saturation conditions. With this and pump number one running, one auxiliary condenser coil and the four condenser test tubes were used to bring the pool down to a subcooled condition (for R-114, approximately  $1^{\circ}\text{C}$  on all three pool thermocouples). Subcooling of the refrigerant was done to ensure the pool had an evenly distributed temperature prior to starting a run. After reaching this subcooled condition, all coolant supply to the condenser was secured. The pool was then allowed to 'heat up' by conduction from the surroundings. Once a saturation temperature of  $2.2^{\circ}\text{C}$  was reached, the instrumented tube(s) (and simulation heaters for test 7) was/were switched on and set to the desired heat flux value.

This lengthy procedure was done to prevent the tubes from prematurely nucleating. The heat flux of the instrumented tubes was then slowly increased at desired intervals by adjusting the rheostat. For increasing heat flux, the data was taken with very small heat flux increments (every 1000 kW/m<sup>2</sup>), waiting at least 5 minutes to attain steady state conditions at each heat flux. At all regions of the boiling curve (and especially near the onset of nucleate boiling), two readings were taken at each heat flux to ensure accuracy. The bundle was continuously visually monitored through the observation windows. Figure 11 shows the tube bundle arrangements used during the experimentation. Test one was with only one instrumented tube turned on at any position within the bundle. Test two was with instrumented tubes one and two active in the bundle. Test three was with instrumented tubes one, two and three active in the bundle. Test four was with instrumented tubes one, two, three, and four active in the bundle. Test five was with all five instrumented tubes active in the bundle. Test six was all five instrumented tubes plus all five pairs of active enhanced heater tubes active in the bundle. Test seven was the same as test six with the addition of all five simulation heaters active. For each data set, the five simulation heaters had the same heat flux as the tubes within the bundle.

#### G. OIL ADDITION

During the bundle experiments, successive amounts of York-C oil were added into the evaporator. Since the weight of the refrigerant in the evaporator was 60.3 kg, the amount of oil corresponding to 1% by weight was measured as 670 ml, 2% 1340 ml etc. The oil was syphoned into the

evaporator via a funnel/hose connection through valve R-3 by reducing the pressure in the evaporator to less than 15 inHg vacuum. Ensuring that no air entered the system, valve R-3 was promptly shut when the desired amount of oil had been added.

#### H. DATA REDUCTION PROCEDURES

The data reduction program "DRP4RH" was used during the experiments for processing the data collected ( see Appendix E for listing). The program was written in HP Basic 3.01 and run on an HP-9000 series computer. The characteristics and capabilities of this software are similar to those provided by Anderson [Ref. 13]. The following modifications were made:

1. Correction for pool height by Chilman [Ref. 3]
2. Installation of new thermocouple at the bottom of the liquid pool (bundle inlet temperature) by Chilman [Ref. 3]
3. The ability to obtain data from one instrumented tube at any position in the bundle.
4. The natural convection correlation of Churchill and Chu [Ref. 31] for a single horizontal cylinder in an 'infinite' liquid pool was added for comparison with experimental data.

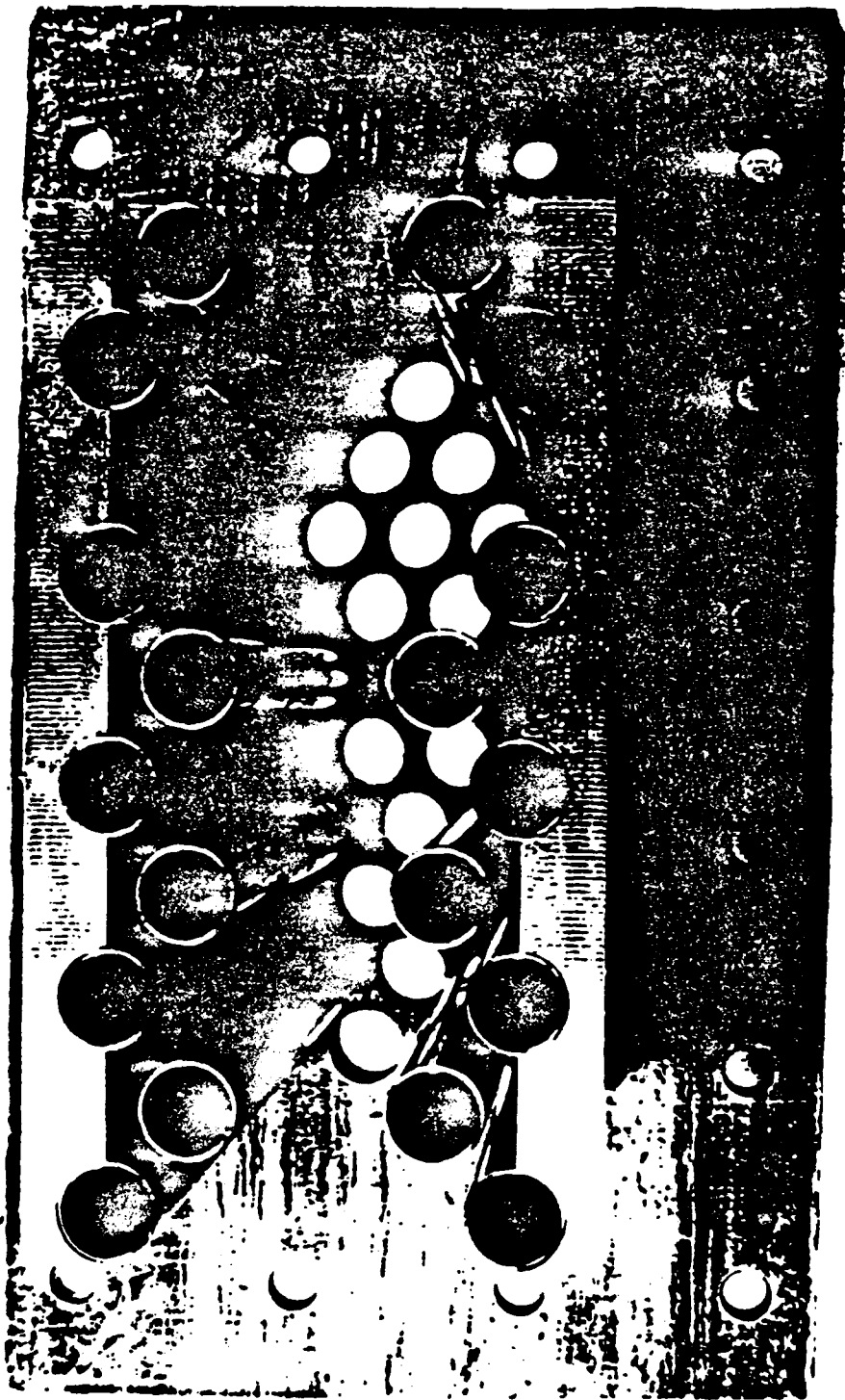


Figure 10. Photograph of Tube Bundle Support Block

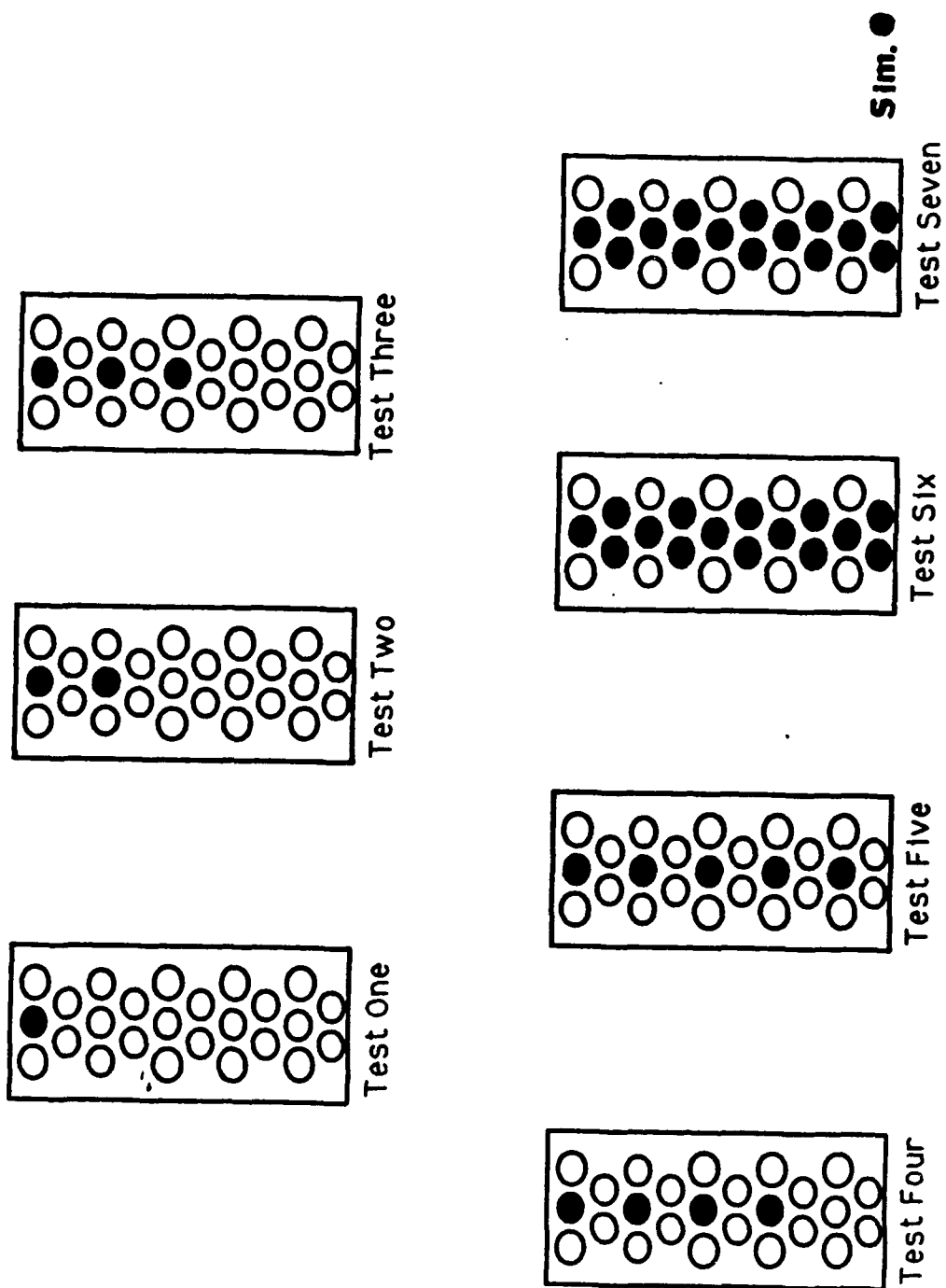


Figure 11. Tube Bundle Arrangements used During Experimentation

## V. RESULTS AND DISCUSSION

### A. INTRODUCTION

The results are presented in four sections with subs-sections as appropriate. The first section discusses the preliminary experiments which led to modifying the experimental start-up procedure to include subcooling. The second section discusses the natural convection effects, nucleate pool boiling phenomena and hysteresis effects within the tube bundle in pure R-114. The third section discusses similar phenomena for R-114/oil mixtures and their effects on the above. The fourth section shows comparisons of data taken during this thesis with previously obtained data at the Naval Postgraduate School.

A list of data files taken during this investigation may be found in Appendix A. All data files used in this thesis use the following filename sequence. Each file is composed of five sets of alpha-numeric characters used to describe the experiment.

First set (2 char.)	Tube Type	TB (Turbo-B)
Second set (1 char.)	Heat Flux	I (Increasing) D (Decreasing)
Third set (2 char.)	Oil Percent	00 (0%) 01 (1%) 02 (2%) 03 (3%) 06 (6%) 10 (10%)
Fourth set (2 char.)	Test Type	01 (test 1) 02 (test 2) 03 (test 3) 04 (test 4)

05 (test 5)  
06 (test 6)  
07 (test 7)

Fifth Set (1 char.)      Additional tests   A-Z (If conducted)

To give an example, the filename TBI0107 means "Turbo-B tube bundle, increasing heat flux, 1% R-114/oil mixture and test number 7". If more detail is desired about a specific data set, see Appendix A. All plot filenames are similar to data filenames except they start with the letter "P". The test numbers are shown in Figure 11 in Chapter IV.

All graphs are plotted showing heat flux ( $W/m^2$ ) along the ordinate (y axis) as a function of wall superheat (K) along the abscissa (x axis). The wall superheat is defined as the difference between the 'corrected' average tube wall temperature (ie. having accounted for depth of thermocouple burial) and the local liquid saturation temperature (corrected for hydrostatic head within the bundle). The heat flux was corrected to account for the heat lost through the unheated tube ends. The heat flux was varied from 600 to 100,000  $W/m^2$  for increasing heat flux. To ensure greater detail at the point of incipience, the heat flux was increased in small steps; these settings varied from test to test. The heat flux values for decreasing experiments were taken at prescribed settings for easy comparison with past experiments and future reference. These heat flux settings were  $1 \times 10^5$ ,  $7.5 \times 10^4$ ,  $5 \times 10^4$ ,  $3 \times 10^4$ ,  $2 \times 10^4$ ,  $1.5 \times 10^4$ ,  $1 \times 10^4$ ,  $7 \times 10^3$ ,  $4 \times 10^3$ ,  $2 \times 10^3$ ,  $1 \times 10^3$   $W/m^2$ . Approximately 30-40 data points were taken for each increasing heat flux run and 20-25 points were taken for each decreasing heat flux run.

## B. PRELIMINARY EXPERIMENTS

After the pure R-113 was removed following Chilman's [Ref. 3] experiments and the apparatus and system cleaned, pure R-114 was added from the storage cylinders. Five tests were conducted using this R-114 and these are shown in Figure 12. The first test (TBI0001A) was test one with the top tube activated. The procedure described by Eraydin [Ref. 28] was followed, but the plot of test TBI0001A and Eraydin's data for test one (also shown in Figure 12) produced significantly different results in the natural convection (NC) region. The data of Eraydin show a greater heat transfer coefficient (lower wall superheat) than test TBI0001A which show results closer to the Churchill/Chu [Ref. 31] correlation (C/C) for natural convection. The only difference in the apparatus between test TBI0001A and Eraydin's experiments was the addition of a third thermocouple at the bottom of the pool. For test TBI0001A, all three pool temperature readings were within  $\pm 0.1$  °C prior to recording data. For the data of Eraydin, only the temperature at the top of the pool could be checked.

Test TBI0001B was thought to be a repeat of test TBI0001A, but for the bottom tube in the bundle (tube 5 only). However, upon observation and investigation, it was found that two tubes (tube one and tube five) were activated due to the way the program DRP4 was set up. Hence the data presented is for tube one (the top tube) with tube five (the bottom tube) activated as well. The program was then modified to obtain data for a single tube (test one) at any position within the bundle.

Test TBI0001C was conducted using the bottom tube (tube five) as a single tube. Again following Eraydin's [Ref. 28] procedure, partial



nucleation was observed immediately, explaining why the data lie well to the left of the Churchill/Chu correlation (ie. a higher heat transfer coefficient). It can be seen that test TBI0001C is in good agreement with the single tube of Eraydin (top tube). The reason for this is probably due to the start-up conditions, which were not carefully monitored for any of these tests.

Test TBI0001D was conducted using only tube three and also followed the procedure of Eraydin. This displayed similar behavior as test TBI0001A (tube one) except that nucleation was delayed, ie. occurred at a higher wall superheat.

All experiments thus far were conducted following Eraydin's procedure for pure R-114. It was next decided to vary his procedure slightly. For test TBI0001E, the pool was first subcooled slightly to 1°C. This ensured that any nucleation sites were deactivated and that the whole pool was at an even temperature. The pool was then brought up to the required saturation temperature. However, partial nucleation was still observed during the run. The plot of TBI0001E is similar to test TBI0001C and Eraydin's test one.

With all of these confusing results, it was decided to empty, clean and recharge the evaporator with fresh R-114. Upon boiling off the 'old' R-114, a small quantity of oil contamination was found in the bottom of the evaporator. This could have been either vacuum pump oil (which may have leaked into the apparatus) or refrigerant oil that entered the system with the R-114 charge (which should be minimal). A third possibility could be oil from previous refrigerant/oil mixture experiments. However, this is not likely since the system had been completely stripped and

cleaned twice since the last mixture tests had been conducted. Samples of each type of oil (vacuum pump oil, miscible refrigerant oil (York-C) and a sample of the contamination) were sent away for analysis and the results were still forthcoming at the time of writing this thesis. From the color of the contamination, it would appear to have originated from the vacuum pump. This would seem to be more logical since Chilman had experienced problems with the vacuum pump.

The system, including the bundle, were cleaned thoroughly and fresh R-114 was added. However, a gas purifier was utilized to ensure that only pure, clean R-114 (with no moisture) was added (see Chapter IV for further details). Test TBI0001F then was conducted following Eraydin's [Ref. 28] procedure with no subcooling and 'ignoring' the bottom pool thermocouple value. The data showed good agreement with Eraydin in the natural convection region, but a lower heat-transfer coefficient in the boiling region. A possible explanation for this lower heat transfer is the fact that each individual tube was fully cleaned prior to adding the new R-114 and the surface characteristics may have been modified in some way.

Test TBI0001G was conducted using the same procedure except the pool was initially subcooled down to  $1^{\circ}\text{C}$  for 30 minutes. This ensured the pool had an even temperature distribution throughout. The data were now much closer to the Churchill/Chu [Ref. 31] correlation. However, some premature nucleation was still observed. Test TBI0001J repeated the above test with the pool temperature subcooled to  $1^{\circ}\text{C}$  for at least one hour to further deactivate any remaining nucleation sites within the bundle prior to starting experiments. The data then agreed with the Churchill/Chu correlation as seen in Figure 12. It became apparent that premature

nucleation could affect the natural convection data significantly. Therefore, for all subsequent tests, this same procedure was adopted with strict observation of the bundle to ensure no premature nucleation occurred.

#### C. PURE R-114 TURBO-B TUBE BUNDLE EXPERIMENTS

##### 1. Test One for Different Tube Positions

The first set of experiments conducted were performance tests in pure R-114. Figure 13 shows increasing heat flux for a single tube within the bundle at different positions (positions 1, 3, and 5) while Figure 14 shows corresponding data (including typical uncertainties) for decreasing heat flux. All three tube positions agree closely with the Churchill/Chu [Ref. 31] correlation in the natural convection region. The difference between position 1 and position 3 and 5 may be that position 1 is affected by the fact that the flow is 'free' to expand after leaving the bundle. This difference may also be due to wall temperature uncertainty due to differences in the fabrication process (see uncertainty analysis Appendix C); however in the natural convection region, this uncertainty is low due to relatively high values of wall superheat. Figure 13 also shows that tube position within the bundle may influence the point of incipience. Bergles and Rohsenow [Ref. 32] have studied the incipient point in more detail. They concluded that nucleation was controlled by a nucleation parameter,  $N$ , given by

$$N = \frac{(\sigma)(T_s)(v_{fg})}{(p_v)(h_{fg})}$$

which creates an incipient boiling superheat given by

$$(T_w - T_s) = 2(N)/r.$$

In the above expression,  $r$  is the local bubble radius. Calculation of the nucleation parameter for pure R-114 showed that as saturation pressure increases, the nucleation parameter decreases. Assuming that the radius of curvature of the forming bubbles is constant (which is reasonable for a Turbo-B surface which has large, regularly spaced cavities), then  $(T_w - T_s)$  also decreases and nucleation may be expected to occur earlier. This certainly seems to be verified in Figure 13 where the incipient point occurs earlier (lower wall superheat) for a lower tube i.e. where there is an increase in the local saturation pressure. You et al. [Ref. 33] also showed a decrease (approx. 30%) in the average incipient superheat as pressure was increased from 1 to 1.5 bar for pool boiling of FC-72 on a single tube, offering some other experimental verification for this conclusion.

Chilman [Ref. 3] conducted test one for R-113 using the top tube only and varied the local saturation pressure by varying the pool height in the evaporator. He found that the point of incipience was delayed when increasing the liquid pool height (i.e. the hydrostatic pressure head). Boundary layer effects due to different liquid circulation patterns may have caused this delay in nucleation and more research is certainly needed to fully understand the influence of pressure on the point of incipience. One experiment that could be conducted would be to vary the pool height, but keep the local pressure at each tube constant by simultaneously varying the vapor pressure above the pool.

Once nucleation occurs, Figure 13 shows that the single tube experiments merge onto a single boiling curve. In this region, there appears to be no effect of hydrostatic pressure head. Figure 14 shows the corresponding decreasing heat flux data for a single tube at the same three positions within the bundle. It shows no significant influence of tube position in the bundle for decreasing heat flux. Note that at low heat flux, the experimental uncertainty in heat flux and wall superheat is the largest (see Appendix C).

## 2. Test Two to Test Seven

Figures 15 to 20 show test two to test seven for increasing heat flux with pure R-114. Also shown for comparison in each figure is the Churchill/Chu [Ref. 31] correlation although this is only truly valid for a single tube in an infinite pool. Figure 15 shows good agreement with the Churchill/Chu correlation in the natural convection (NC) region and shows no effect of the lower tube on the upper tube. The incipient point occurs approximately at the same wall superheat for both tubes; once boiling the lower tube has the higher heat-transfer coefficient. This is contrary to the results obtained by Chilman [Ref. 3] and Anderson [Ref. 13] with pure R-113, where the higher tube had the better heat transfer. The reason for this difference is not known, but may be due to the explosive nature of incipience for R-114 compared to the more gradual partial incipience for R-113. For R-114 experiments, the pool was subcooled by 1 °C for only about hour while for the R-113 experiments, the pool was left in a subcooled state since the previous experiment (for R-113 experiments, the pool is 'heated up' to saturation conditions). This

difference in subcooling may significantly affect the nature of the observed incipience. Further research should be conducted at the incipient point to address some of the questions. Figure 16 for three tubes activated shows similar behavior as Figure 15 (ie. during nucleate boiling, the lowest tube has the highest heat-transfer coefficient). Also, Figure 16 shows that the lowest tube seems to nucleate last. Figures 17 and 18 for four and five tubes activated show similar trends in both the NC and boiling regions. It appears that the tubes nucleate in order down the bundle (ie. the top tube nucleates at the lowest wall superheat and the bottom tube nucleates at the highest wall superheat). For tests six and seven (Figures 19 and 20 respectively), the maximum controllable heat flux was less than tests one through five due to the use of smooth tubes in the condenser limiting the condensate rate (and hence pressure) in of the vapor space (if enhanced tubes had been used, this could have been increased). Figure 19 (test six) is consistent with the above trends. Furthermore, the effect of activating the whole bundle seems to cause the lowest tube to nucleate at a lower heat flux and wall superheat. It also appears that there may be some influence of tube position in the boiling region; however, this is probably due to inaccuracy in the wall temperature measurements (see Appendix C). When the simulation heaters are also activated (test seven, Figure 20) the trends in the NC region are similar (ie. no effect of lower tubes on upper tubes). Full nucleation of the bundle however, seems to occur earlier.

Figure 21 shows the data from tube one for all seven tests with increasing heat flux. This figure is of more fundamental interest as it shows the same tube under different bundle conditions. It therefore gives

a better direct comparison of the effect of heated lower tubes as any uncertainty in the tube wall measurements (the largest error in the experimental data) is the same for each test (ie. any effects seen in the data are bundle effects). In the NC region, tube one alone (test one) is somewhat different. This may be due to 'expansion' of the flow as it leaves the top of the bundle (ie. where the velocity of the flow has slowed down) or due to convective effects by the addition of another tube. For test two, Figure 21 shows an effect of the lower tube on tube one performance in the NC region. For test three and all subsequent tests no further improvement is seen. It appears, therefore that in the natural convection region, an upper tube is affected by a lower tube directly below; however, when additional lower tubes are heated, there is no further increase in performance of the top tube. There is also no effect on the incipient point (apart from test one mentioned above). In the high heat flux boiling region, there is also little enhancement due to the lower tubes. This is to be expected in an enhanced tube bundle, where the total heat transfer at high heat fluxes is primarily due to nucleation from the tube surface itself, rather than from convection around the surface from the tubes below.

Figures 22 to 27 show tests two to seven for decreasing heat flux in pure R-114. When comparing tube one to tube two, Figure 22 shows a increase in heat transfer performance of tube one by tube two in the boiling region while Figure 15 (increasing heat flux) showed the opposite effect. The most probable reason for this crossover is that these two experiments (TBI0002) and (TBD0002) were conducted on different days and startup procedures were slightly different. For TBI0002 (increasing heat

flux), the test was conducted as outlined in Chapter IV section F (ie. subcooled to 1 °C, gradually heated up with data taken over a period of approximately 4 hrs). For TBD0002 (decreasing heat flux), the pool was subcooled to 1 °C, and then tube one and two were turned on to the highest heat flux ( $10^5 \text{ W/m}^2$ ) and allowed to heat up for 30 minutes. The total time boiling for TBI0002 at the highest heat flux was therefore less than for TBD0002. For all other experiments, increasing followed by decreasing runs were conducted on the same day approximately 15 minutes apart. More research should be conducted to investigate nucleation site activation/deactivation.

At high heat fluxes for test three, Figure 23 shows no heat transfer performance improvement between the tubes. However, at low heat fluxes, there does appear to be an improvement on tube one and two from tube three. Figures 24 to 27 show similar trends at high and low heat fluxes (ie. the top tubes are further enhanced by lower tubes at low heat fluxes). It should also be noted that the lowest tube in any specific decreasing heat flux test had the worst performance.

Figure 28 compares tube one only for tests one to seven for decreasing heat flux. As stated above, there appears to be a definite tube enhancement at low heat fluxes with little or no enhancement at high heat fluxes. This is probably due to convective effects which tend to increase the heat transfer performance of the upper tubes due to the presence of lower tubes (ie. bubbles coming from the lower tubes impinge and slide over the upper tubes and increase the heat transfer). At high heat fluxes, on the other hand, all the tubes are nucleating so vigorously that these 'sliding' bubbles have little or no noticeable affect on the



overall performance. This supports the hypothesis of Cornwell [Ref. 7] that total heat transfer in a bundle is due to a summation of convective and nucleation heat transfer phenomena. Similar trends were found by Anderson [Ref. 13] and Akcasayar [Ref. 25] for smooth and finned tube bundles respectively (using the same apparatus) and also by Arai et al. [Ref. 20] for a Thermoexcel-E tube bundle. However, Akcasayar [Ref.] did not find such an enhancement effect for a High Flux tube bundle indicating that at low heat fluxes, a porous coated surface already has a significant number of active nucleation sites such that impinging bubbles from below have little or no added effect. Turbo-B is more similar to a Thermoexcel-E surface and at low heat fluxes, these two types of surface obviously exhibit different nucleation characteristics to those of a porous coated tube.

#### D. R-114/OIL MIXTURES TURBO-B TUBE BUNDLE EXPERIMENTS

##### 1. Tests with 1% and 2% oil

Only four experiments were conducted with a 1% and 2% R-114/oil mixture. These were tests one and seven for both increasing and decreasing heat flux; no experiments were conducted for tests two through six. Figure 29 shows test one at 1% oil concentration for increasing and decreasing heat flux, clearly showing a hysteresis pattern. Compared with pure R-114 (Figures 13 and 14), Figure 29 shows no apparent effect of oil on the heat transfer in either the NC or boiling regions.

Figure 30 shows test seven for increasing heat flux (1% oil). Compared with Figure 20 (pure R-114), there are similar trends (ie. no

effect in the NC or boiling regions). The tubes again appear to be nucleating 'in order' down the bundle, as found with test seven in pure R-114. For decreasing heat flux, Figure 31 shows similar trends to test seven in pure R-114 (Figure 27). Thus a 1% oil concentration appears to have little or no effect on bundle performance for both increasing and decreasing heat flux.

Figure 32 shows test one for a 2% oil concentration for increasing and decreasing heat flux. Figures 33 and 34 show test seven for increasing and decreasing heat flux respectfully for 2% oil concentration. All three graphs (Figures 32 to 34) are similar to those for pure and 1% oil concentrations, showing that 2% oil also has little effect on overall bundle heat transfer performance.

## 2. Tests with 3% oil

Nine experiments were conducted with a 3% R-114/oil mixture. In addition to test one and seven (conducted for both increasing and decreasing heat flux as before), tests two through six were conducted for decreasing heat flux only. Figure 35 shows test one with 3% oil for both increasing and decreasing heat flux. Again, the figure clearly shows hysteresis effects between the increasing and decreasing experiments. As with previous oil percentages (Figures 13, 14, 29, and 32), it shows there is no apparent effect of oil in the NC region, similar to previous test one data for other oil percentages. However, at the highest heat flux ( $100 \text{ kW/m}^2$ ) there is an increase in the heat transfer of about 10%. This is similar to the increases found by Burkhardt and Hahne [Ref.23] in a finned tube bundle and Arai et al. [Ref. 20]. Figure 36 shows test seven

for increasing heat flux. The Churchill/Chu [Ref. 31] correlation for pure refrigerant is plotted for comparison only. Agreement is good, demonstrating that in the NC region, in addition to there being no effect of tube position, there is also no apparent effect of oil concentration on the heat-transfer coefficient. As before, the tubes appear to be nucleating 'in order' (ie. top tube nucleates first with the bottom tube nucleating last).

Figures 37 to 42 show data from tests two to seven for decreasing heat flux only. All show no effect of lower tubes on upper tubes (within the bundle) in the boiling region at high heat fluxes (the small amount of scatter is probably due to inaccuracies in the wall temperature measurements). Each successive figure shows that the lowest tube has the lowest heat-transfer coefficient; this tube is then enhanced by the activation of tubes below it. Again it should be noted that the experimental uncertainty is larger at low heat fluxes. At all oil concentrations, tube five is seen to have the lowest heat transfer performance. According to Chilman [Ref. 3], tube five had the highest uncertainty in the wall temperature measurements and this might be the cause of this discrepancy.

If one compares Figure 42 for 3% oil with Figure 28 for pure R-114, it can again be seen that there is a small increase in the bundle heat-transfer coefficient for the R-114/oil mixture at the highest heat fluxes. For all tests with oil added, significant foaming was observed at the pool surface and this may be the cause of this increase in heat transfer. Schlager et al. [ref. 21] in their review article point out that for certain conditions (typically low pressure and high heat flux),

the heat-transfer coefficient increases at low oil concentrations; they attributed this to foaming. Figure 43 compares test one to seven for tube one for decreasing heat flux. As before with pure R-114 (Figure 28), there appears to be a definite increase in performance of the upper tubes by lower tubes at the low heat fluxes due to convection effects, with little or no such increase at high heat fluxes.

### 3. Tests with 6% oil

The same nine tests as with 3% oil were conducted with a 6% R-114/oil mixture. Figure 44 shows test one for both increasing and decreasing heat flux. It clearly shows a hysteresis 'loop' between increasing and decreasing experiments. In comparison with other oil concentrations, the point of incipience occurs at a slightly lower heat flux. There also appears to be a small degradation in performance (10-15% compared with 3% oil concentration) at the highest heat flux (100 kW/m<sup>2</sup>) due to the oil, but there is no apparent effect in the NC region. Figure 45 shows test seven for increasing heat flux. As before, there is no apparent effect of oil on the heat transfer in the NC region and the tubes appear to be nucleating 'in order'. The point of incipience also seems unaffected by the presence of the oil.

Figures 46 to 51 show tests two to seven for decreasing heat flux. At the highest heat fluxes, there is a similar small degradation in the heat transfer as found with test one (10-15%) when compared with a 3% oil concentration (Figures 37 to 42). When compared with pure R-114 (Figures 22 to 27), there is neither enhancement nor degradation, indicating that any enhancement provided by 3% oil is offset by 6% oil.

At low heat fluxes, the data are not only very similar to that for pure refrigerant, but also to the other R-114/oil mixtures (ie. at low heat fluxes, there is no effect on heat transfer at any oil concentration). Figure 52 compares tests one to seven for tube one for decreasing heat flux. As before, there appears to be the same convective enhancement at low heat fluxes with no enhancement (due to the successive activation of lower tubes within the bundle) at high heat fluxes.

#### 4. Tests with 10% oil

The same nine tests were repeated for an R-114/oil mixture with 10% oil. Figure 53 shows test one for both increasing and decreasing heat flux. Incipience occurred at a slightly heat higher flux than both 3% and 6% oil concentrations indicating that there appears to be no systematic increase or decrease in this point with increase in oil concentration. More importantly, there is a significant decrease in the heat transfer at the highest heat fluxes (20%) when compared with pure R-114. This is probably due to the re-entrant channels becoming 'clogged' with oil as the R-114/oil mixture is 'transported' to the surface at a high rate. Figure 54 shows test seven for increasing heat flux. As before, this shows that the NC region is unaffected by either oil concentration or lower tubes in the bundle. At the highest heat fluxes available ( $40 \text{ kW/m}^2$ ) there appears to be little decrease in the bundle performance (when compared to pure R-114) due to the oil. This indicates that at typical evaporator operating heat fluxes, the presence of oil does not significant effect the heat transfer enhancement process. At higher

heat fluxes, however, the effect of oil appears to be very significant as seen in Figure 53.

Figures 55 to 60 show test two to test six for decreasing heat flux with 10% oil. At low heat fluxes, there seems to be no effect of the oil on the local heat transfer performance. However, at high heat fluxes, there is a significant decrease in performance. Interestingly, if one compares Figures 53, and Figures 55 to 58 at high heat fluxes, the lowest activated tube in the bundle is significantly degraded. The effect of activating a lower tube significantly enhances the heat transfer from the tube directly above and (to a lesser degree) the tubes even higher in the bundle. This may be due to the vigorous boiling action of lower tubes partly 'scouring' the oil rich layer which 'blankets' the upper tubes. This effect was also noticeable with the High Flux bundle (Akcasayar [Ref. 25]).

Figure 61 compares tube one for tests one to seven for decreasing heat flux. If one compares Figures 26 (0%), 43 (3%), 52 (6%) and 61 (10%) for tube one for all seven tests, it is clear that at low heat fluxes, the heat transfer coefficient is similar, regardless of oil concentration. Furthermore, convective effects are consistent and provide similar enhancements in heat transfer performance for all concentrations. At high heat fluxes at 0, 3, and 6% oil concentrations, there is little enhancement due to activation of lower tubes. However, at 10%, there does appear to be a small heat transfer enhancement due to activation of lower tubes. This was attributed above to increased 'scouring' of the oil from the vicinity of the Turbo-B surface by the increase in bubble activity as more tubes are activated within the bundle. However, for a practical

operating heat flux range between 15 and 30 kW/m<sup>2</sup>, there is no significant degradation in heat transfer performance for an oil concentration of up to 10%.

#### E. COMPARISON OF R-114/OIL MIXTURE EXPERIMENTS

Figures 62 and 63 compare tube one from test one for increasing and decreasing heat flux for all oil concentrations. Figure 62 shows no effect of oil in the NC region, but some degradation in the boiling region. The correlation of Churchill/Chu is included for comparison. The incipient point appears relatively random, indicating no early or delayed nucleation caused by the presence of oil. Figure 63 shows similar degradation with a significant effect of the oil (20% decrease in the heat transfer from 0% to 10% oil) at the highest heat fluxes.

Figures 64 and 65 compare tube one from test seven for increasing and decreasing heat flux for all oil concentrations. As compared to tube one test one (Figures 62 and 63), the presence of oil has some degradation effect on the heat transfer performance (15%) in the NC region; this may be due to a change in the mixture properties which would tend to increase the wall superheat slightly as shown. As with Figure 62, Figure 64 shows that the incipient point appears relatively random. Figure 65 shows similar trends to Figure 63 (ie. no effect of oil at high heat fluxes), but shows convective effects at low heat fluxes. This was expected and previously reported (Figures 28, 43, 52, and 61).

Figures 66 and 67 show the average bundle heat-transfer coefficient (ie. an average of all five instrumented tubes) as a function of heat flux for test seven for increasing and decreasing heat flux respectively at all

oil concentration. The data are from the same data set as that shown in Figures 64 and 65. Comparing Figures 64 and 66, degradation is seen in the NC region (15%) due to the change in mixture properties as mentioned above. However, at a practical operating heat flux range between 15 and 30 kW/m<sup>2</sup>, the presence of up to 10% oil causes no degradation in bundle performance as seen. These trends over this heat flux range were similar to that found for a High Flux tube bundle (Akcasayar [Ref. 25]). Comparing Figures 65 and 67, similar trends (ie. no significant effect of oil) are found. However, due to the limit in maximum controllable heat flux for test seven, data at 'higher' heat fluxes ( up to 10<sup>5</sup> W/m<sup>2</sup>) could not be obtained (as mentioned earlier). As shown in Figures 62 and 63, there may be a significant degradation in the heat transfer performance at these higher heat fluxes.

#### F. COMPARISON WITH PREVIOUS NPS DATA

Figure 68 shows a comparison between the present data for a Turbo-B bundle, the data of Anderson [Ref. 13] for a smooth tube bundle and the data of Akcasayar [Ref. 25] for both a 19 fpi and High Flux tube bundle in R-114. For clarity, only test one (tube one) for a decreasing heat flux in pure R-114 has been shown. Figure 68 shows that the Turbo-B tube has a significantly lower heat-transfer coefficient than the High Flux tube at all heat flux. This is surprising since Sugiyama [Ref. 34] showed that in the single tube apparatus, the Turbo-B tube was the best performer. The reason for this difference in behavior is not known. Also, all of the data appear to be parallel to each other; one may expect the enhanced tubes to have a different slope to a smooth tube due to the greater amount of



nucleation. At the highest heat fluxes, Turbo-B and the 19 fpi tube appear to have a similar heat transfer performance. However, the finned tube heat flux is based on the root diameter; if the actual finned area had been used, then the heat flux would be significantly lower. Figure 68 shows that the heat transfer enhancement given by the Turbo-B tube when compared to a smooth tube is about three at high heat fluxes and increases to about five at low heat fluxes.

Figures 69 and 70 compare the average bundle heat-transfer coefficient (ie. test seven) for a given oil percentage to that with no oil for all four tube bundles at heat fluxes of 15 and 30 kW/m<sup>2</sup> respectively. 15 and 30 kW/m<sup>2</sup> were chosen as being representative of the lower and upper limits of heat fluxes used in practical Naval evaporators. At 15 kW/m<sup>2</sup>, Figure 69 shows large enhancements for the smooth and finned tube bundles for all oil concentrations, especially at the lower oil concentrations. However, the Turbo-B and High Flux tube bundles show a degradation in the heat-transfer coefficient at all oil concentrations (approximately 5-10% at low oil concentrations dropping to nearly 25% at 10% oil for the High Flux bundle). At the higher heat flux (30 kW/m<sup>2</sup>), Figure 70 shows similar trends as Figure 69. However, the High Flux bundle now exhibits a 40% decrease in the average bundle heat-transfer coefficient at 10% oil.

Figures 71 and 72 compare the average bundle heat-transfer coefficient (ie. test seven) for each enhanced tube to that for the smooth tube bundle (tested by Anderson [Ref. 13]) for all oil concentrations at heat fluxes of 15 and 30 kW/m<sup>2</sup> respectively. At 15 kW/m<sup>2</sup> with pure R-114, Figure 71 shows an enhancement factor of 3.7 for the Turbo-B tube bundle. This enhancement decreases slowly with increasing oil percentage to a factor of

about 2.5 at 10% oil. This agree very closely with the 19 fpi bundle. The High Flux bundle exhibits much larger enhancements, from over 6 at 0% oil to just over 3 at 10% oil. At  $30 \text{ kW/m}^2$  with pure R-114, Figure 72 shows an enhancement of 3.8 for the Turbo-B tube bundle, decreasing to about 3 at 10% oil. This again agrees closely with the 19 fpi bundle. It should be noted that the High Flux bundle enhancement has decreased to a similar value and gets worse than the other bundles as the heat flux is further increased.

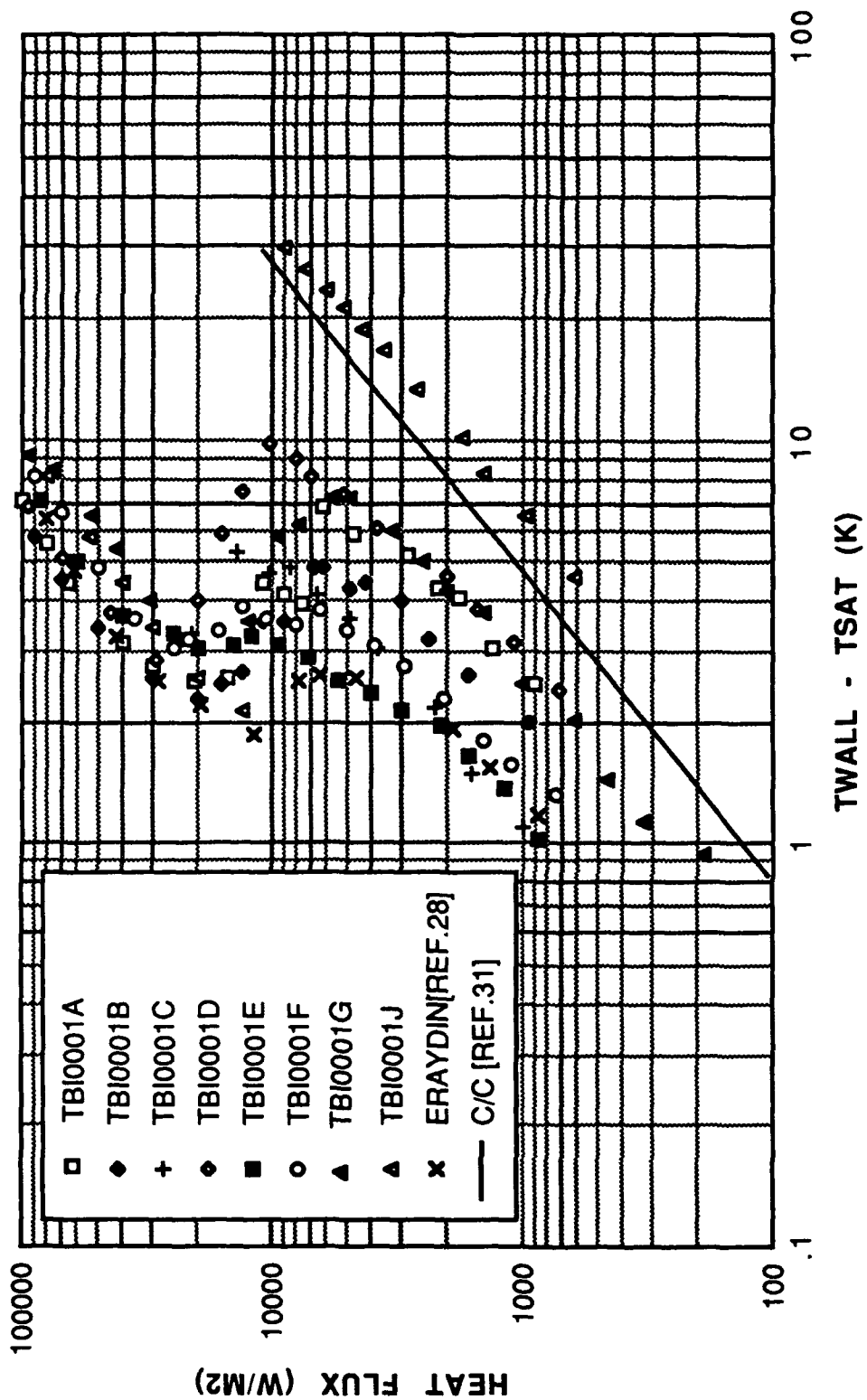


Figure 12. Performance of Test One For Preliminary Experiments

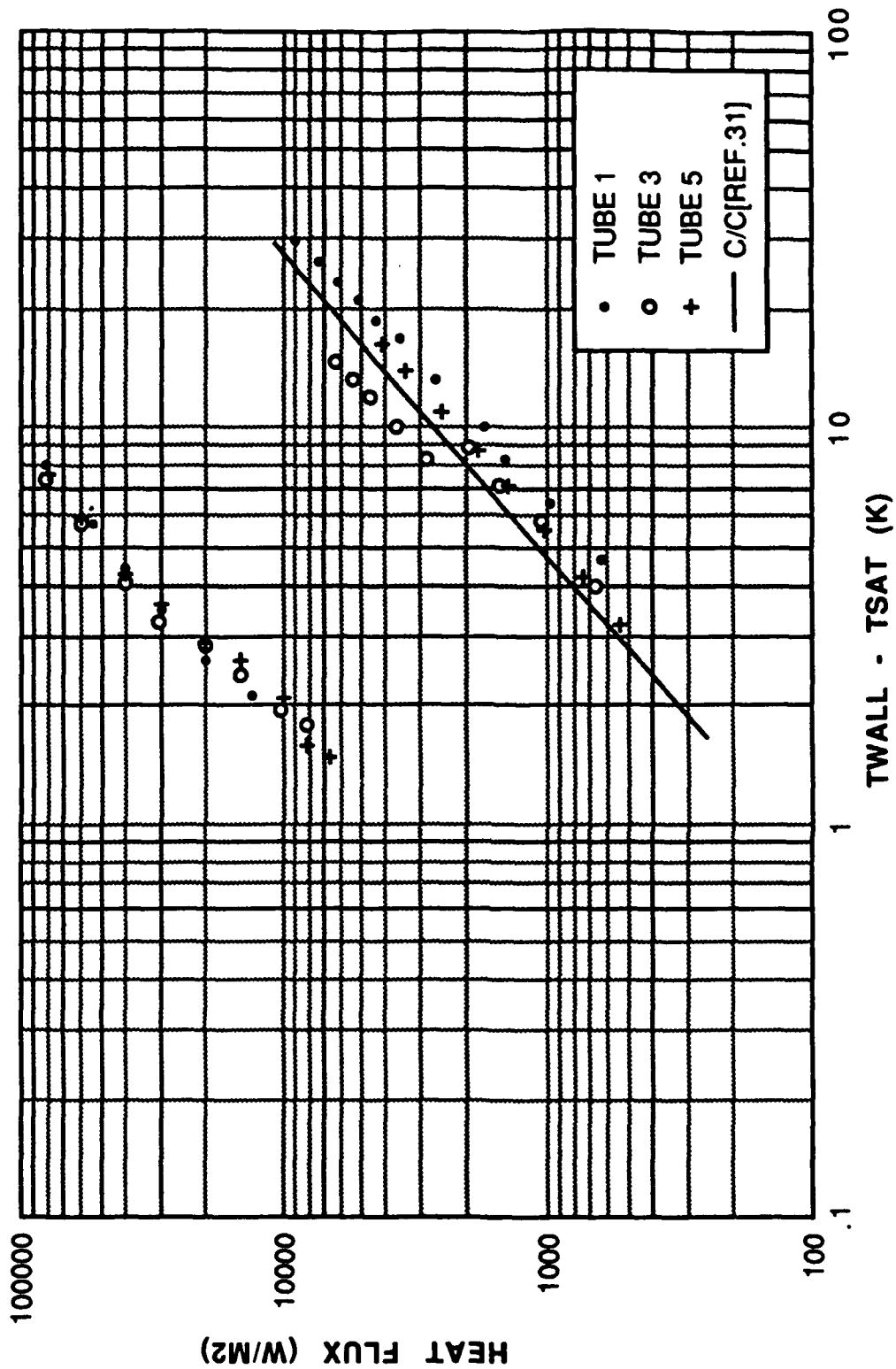


Figure 13. Performance of Test One at Various Tube Positions for Increasing Heat Flux

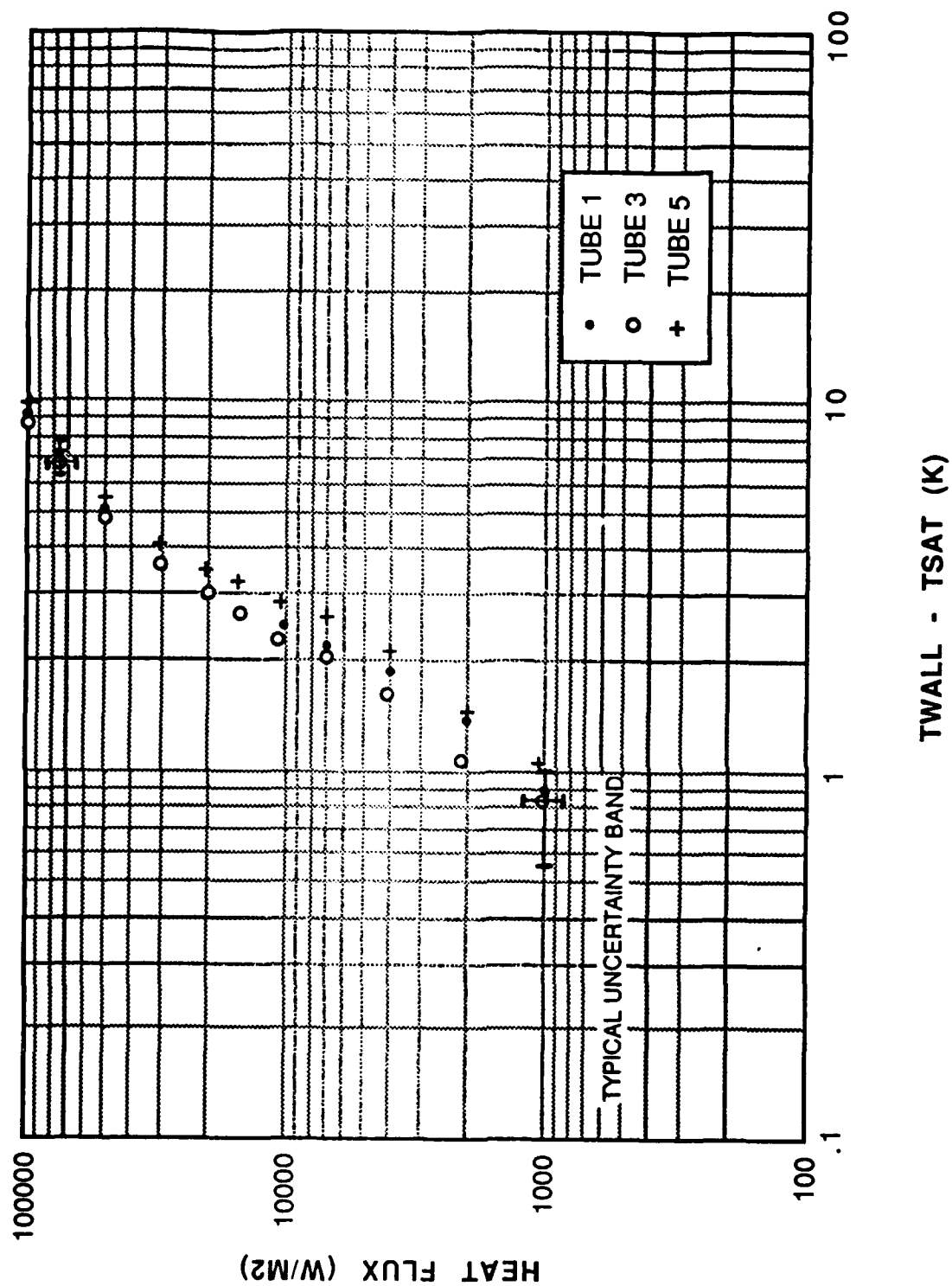


Figure 14. Performance of Test One at Various Tube Positions for Decreasing Heat Flux

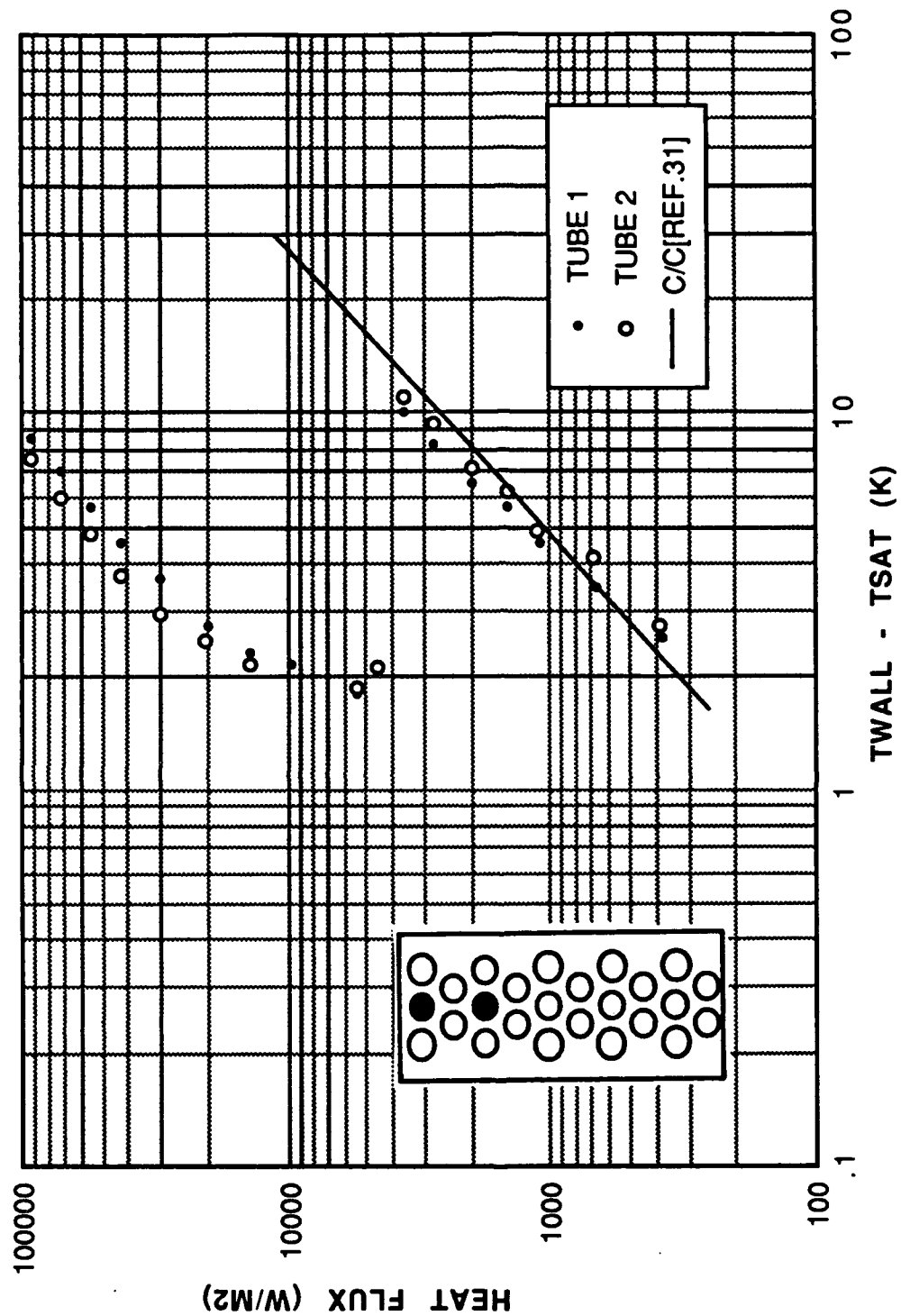


Figure 15. Performance of Tubes 1 and 2 for Increasing Heat Flux in Pure R-114

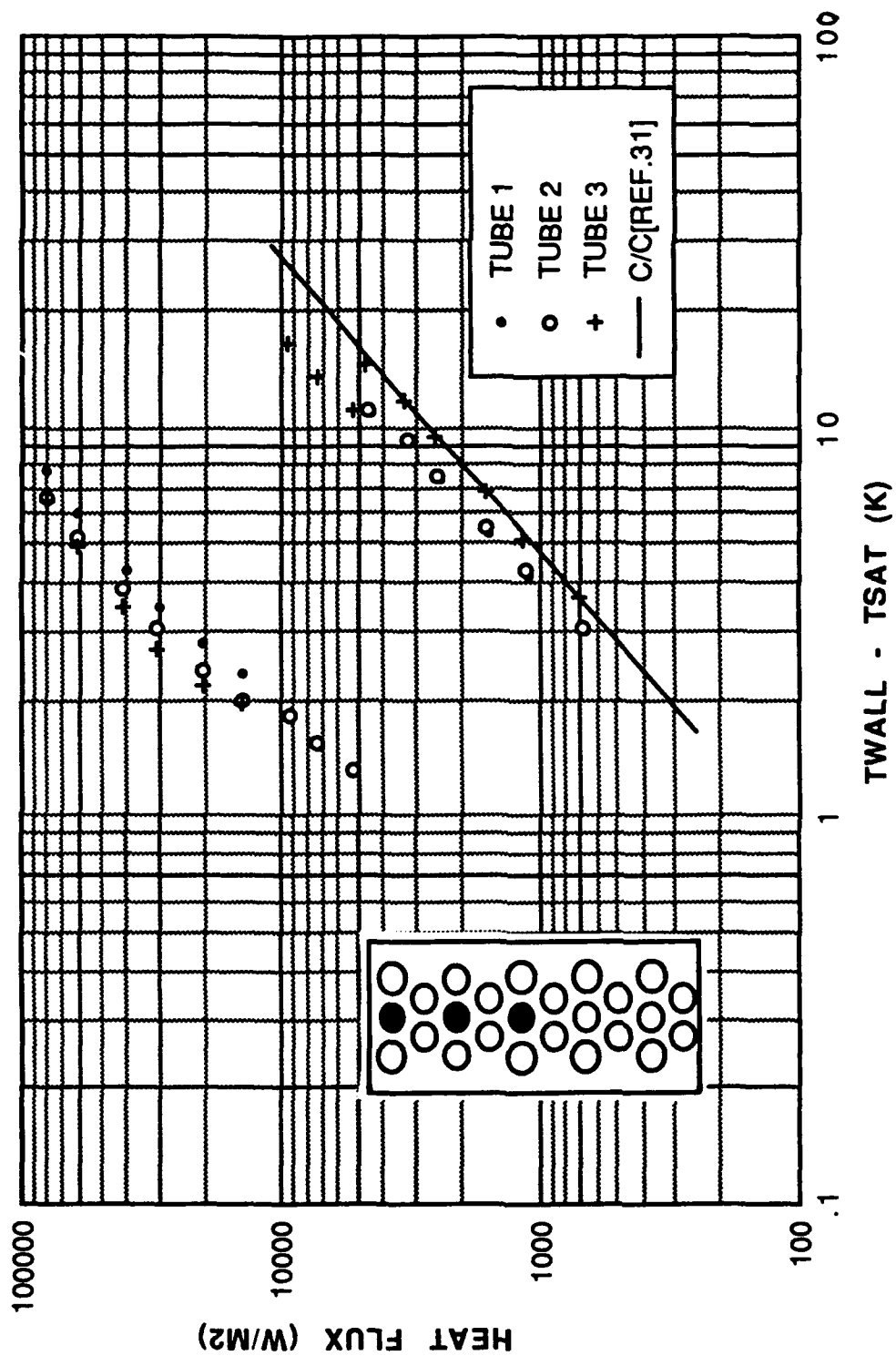


Figure 16. Performance of Tubes 1, 2, and 3 for Increasing Heat Flux in Pure R-114

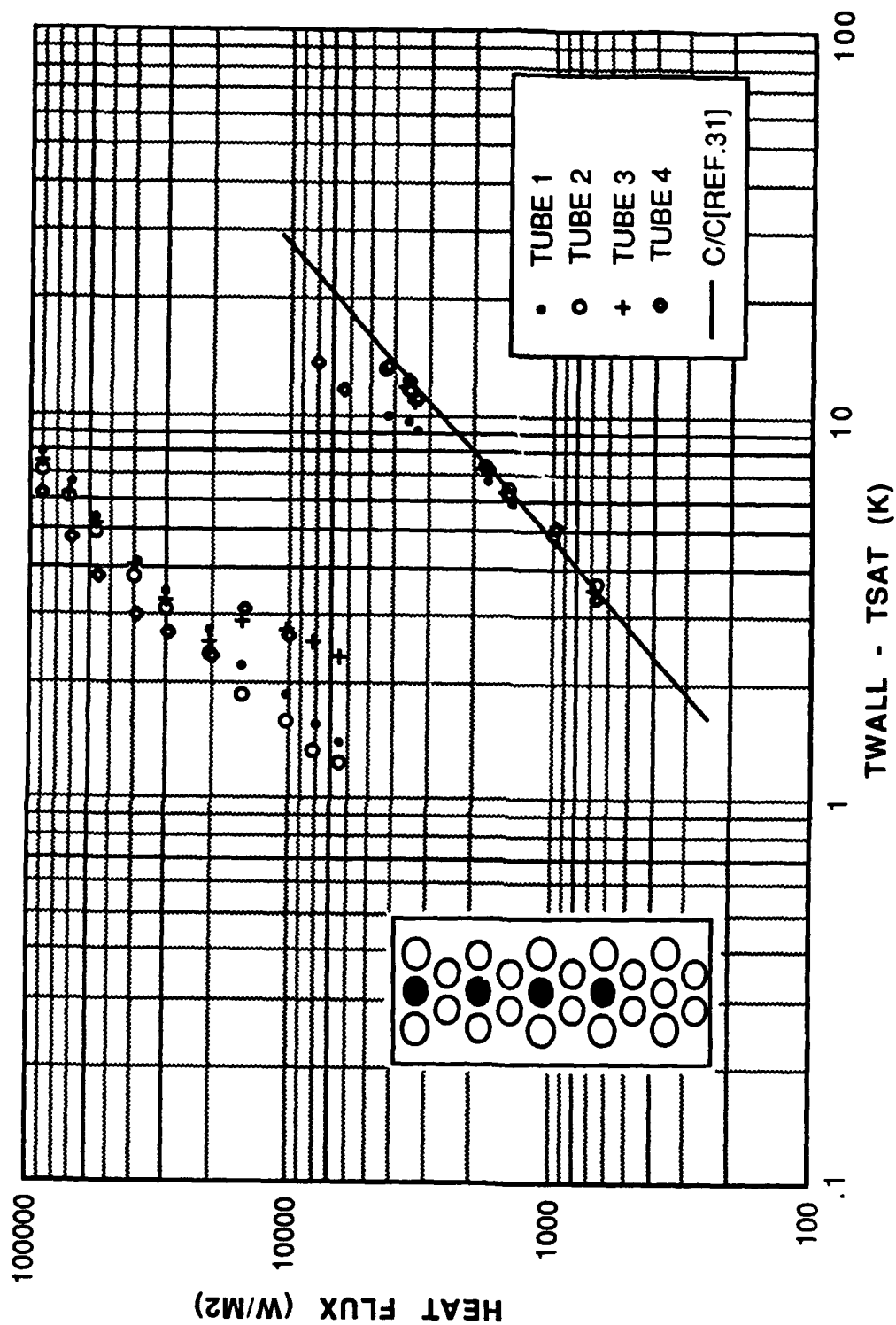


Figure 17. Performance of Tubes 1, 2, 3, and 4 for Increasing Heat Flux in Pure R-114



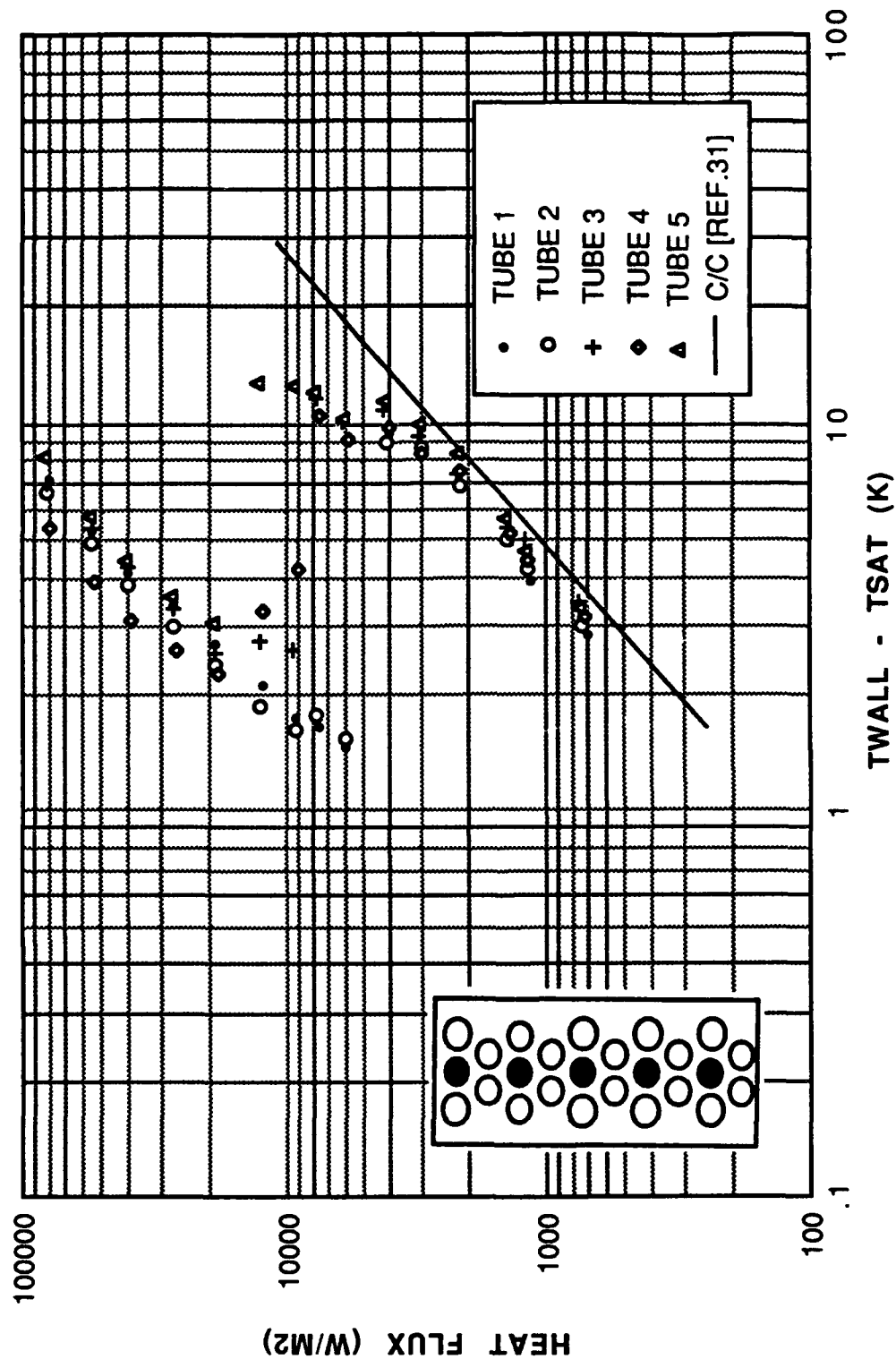


Figure 18. Performance of All Five Tubes for Increasing Heat Flux in Pure R-114

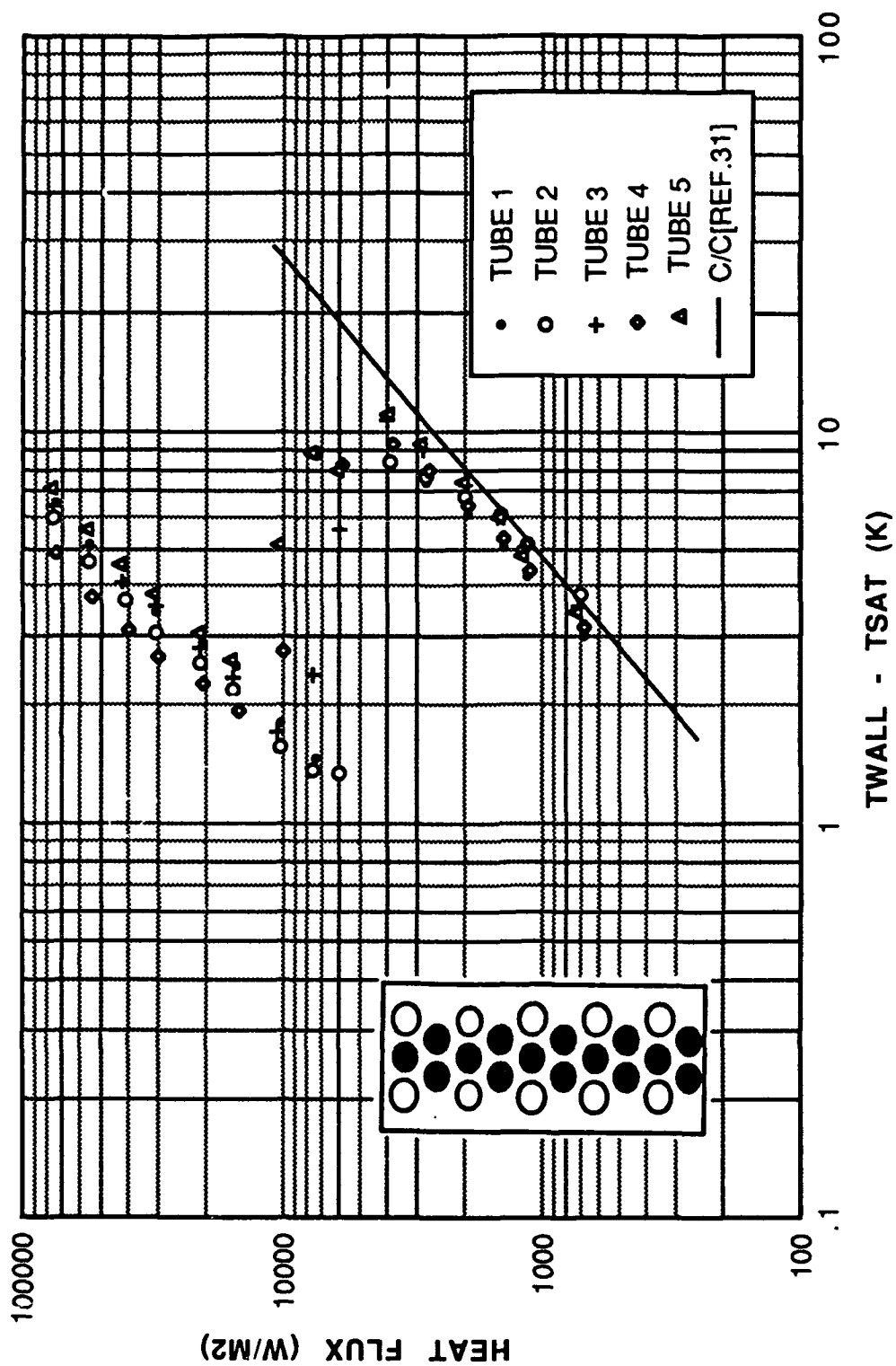


Figure 19. Performance of All Five Tubes with Active Pairs for Increasing Heat Flux in Pure R-114

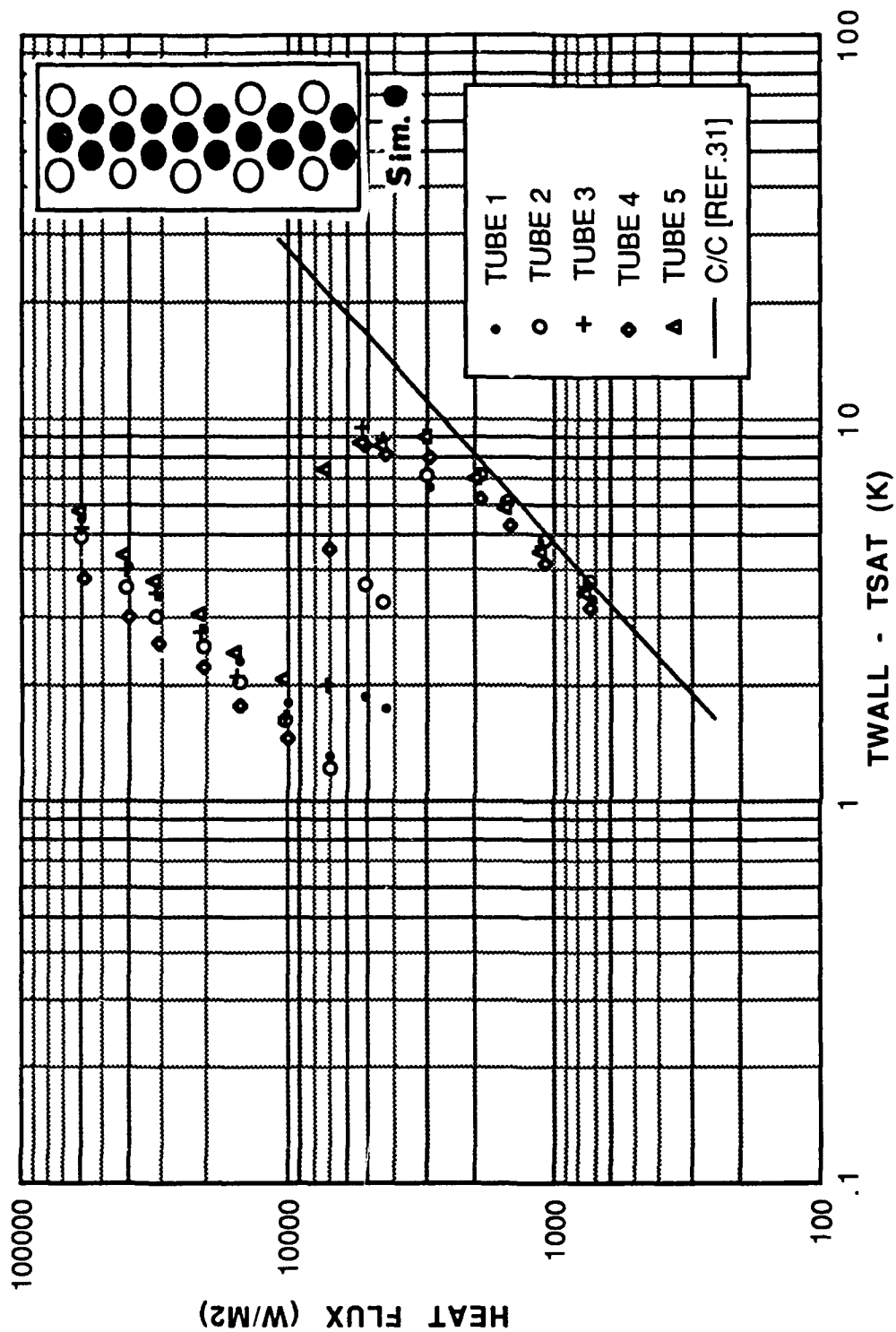


Figure 20. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in Pure R-114

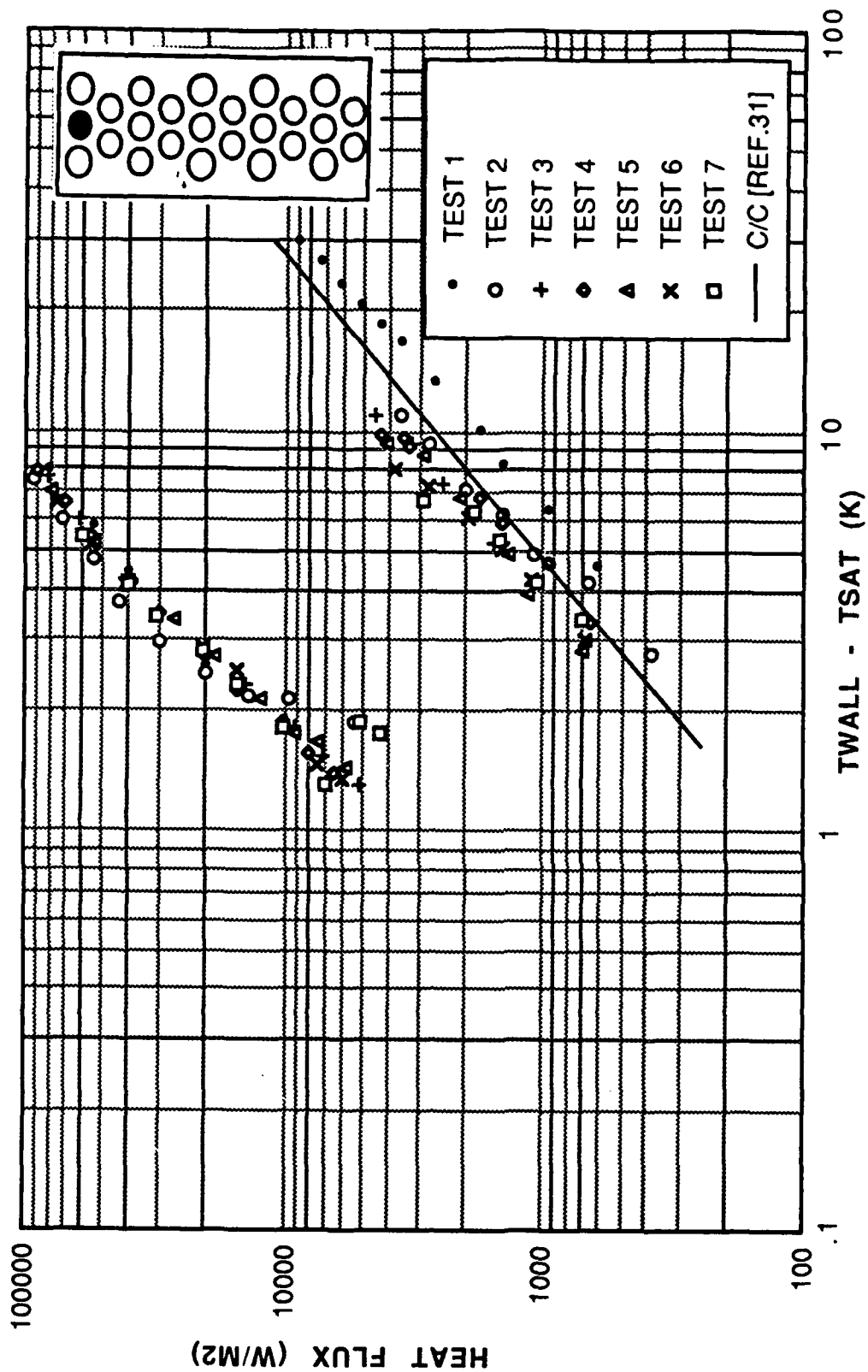


Figure 21. Comparison of Tests One to Seven for Tube 1 for Increasing Heat Flux in Pure R-114

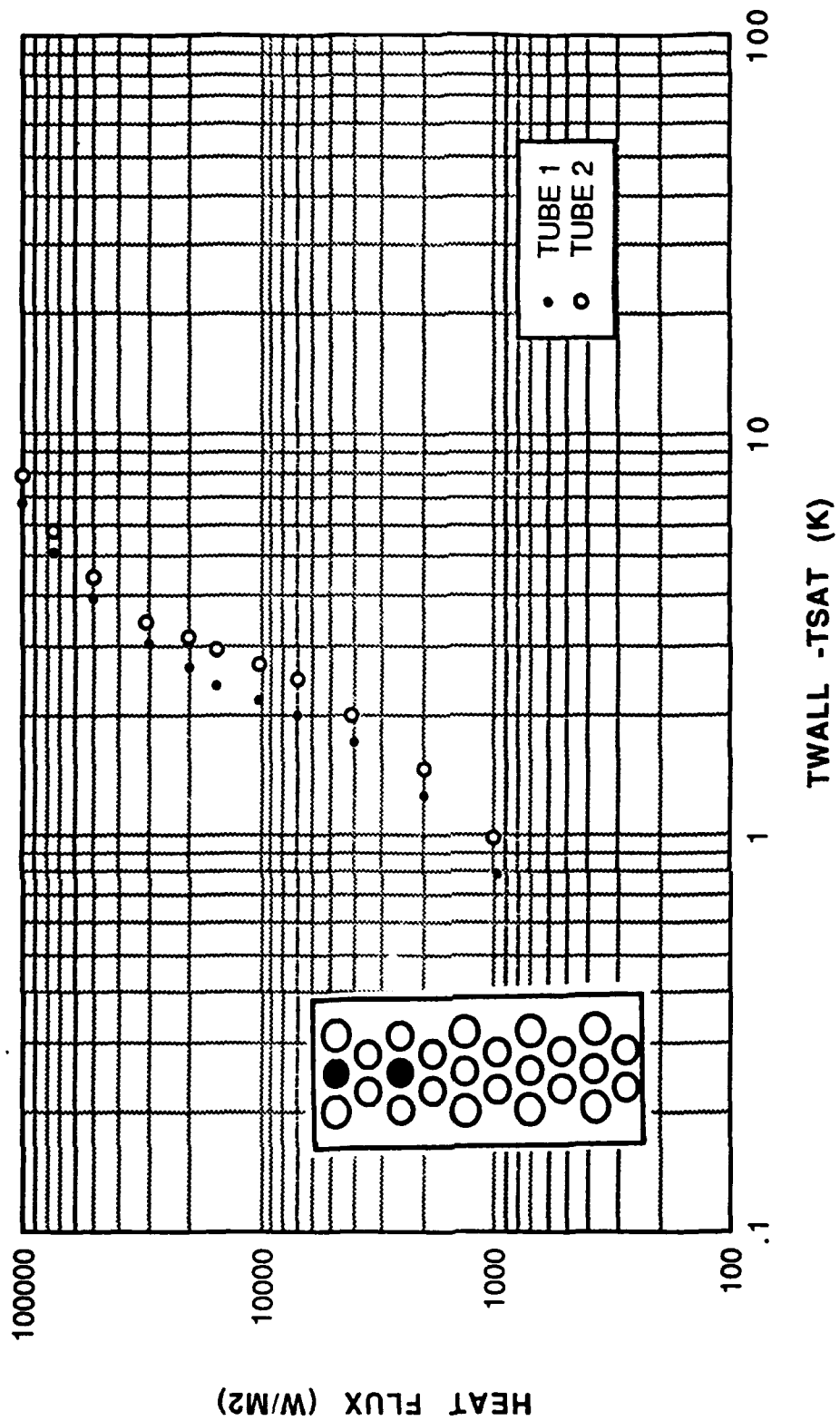


Figure 22. Performance of Tubes 1 and 2 for Decreasing Heat Flux in Pure R-114

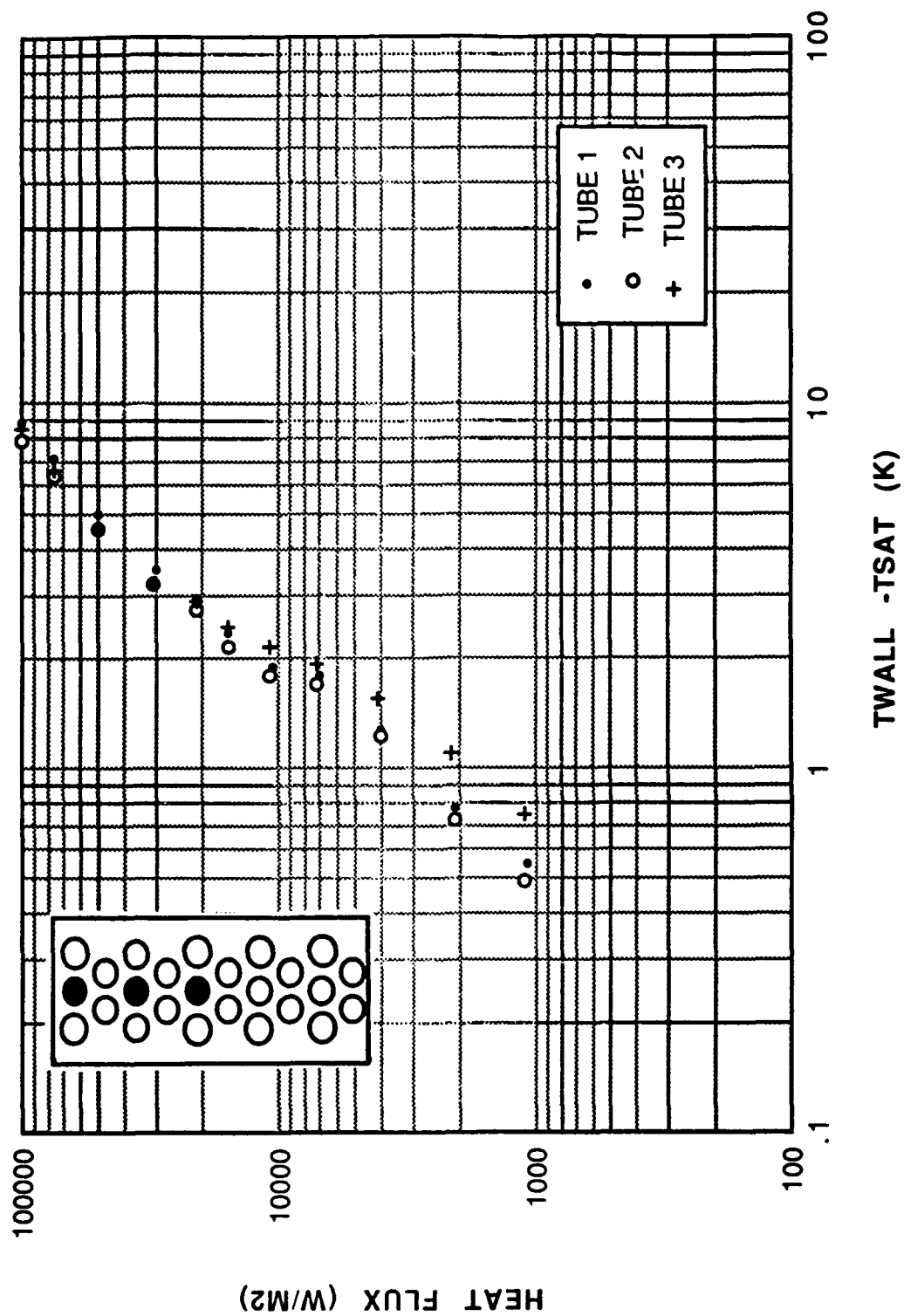


Figure 23. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in Pure R-114

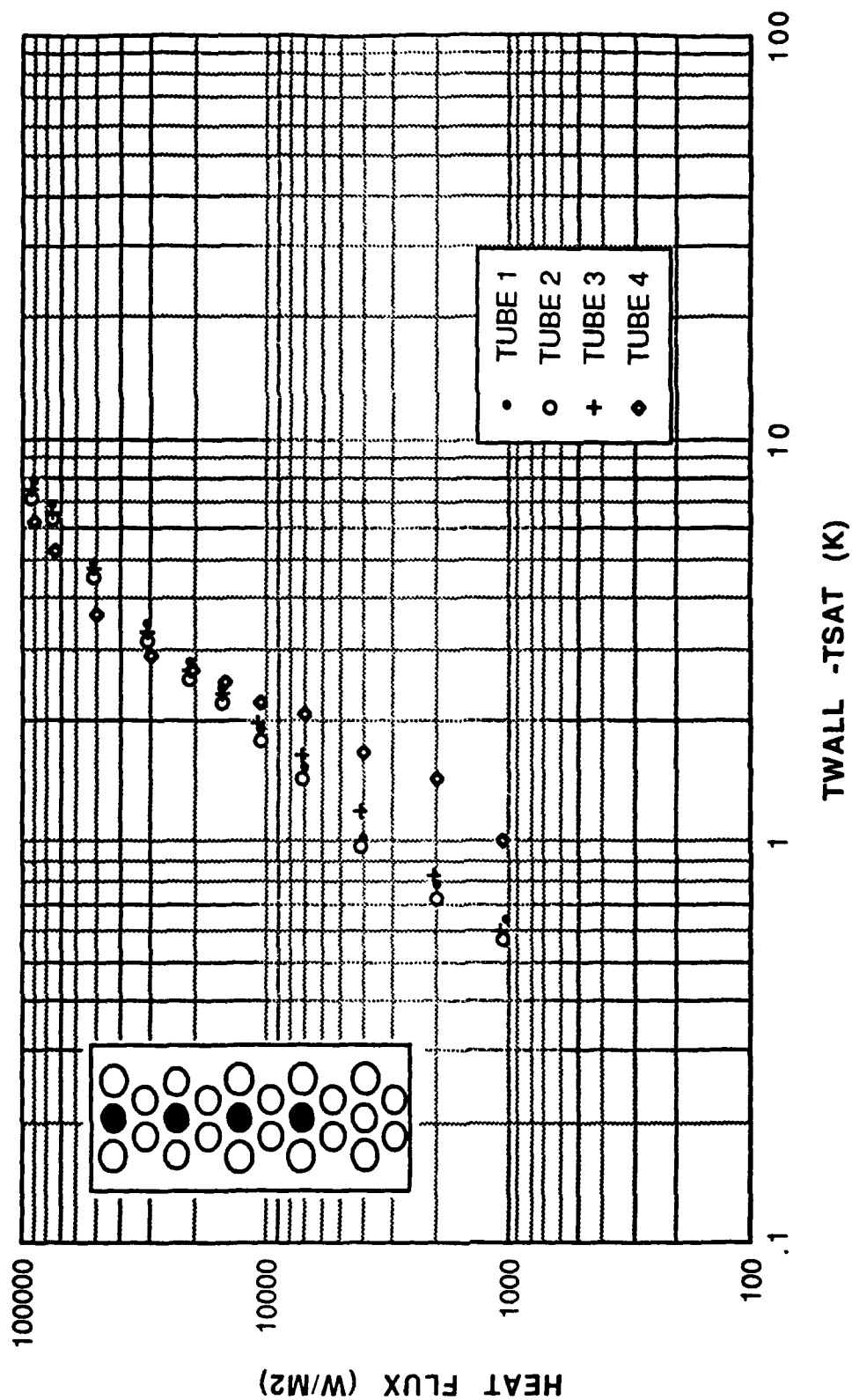


Figure 24. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in Pure R-114

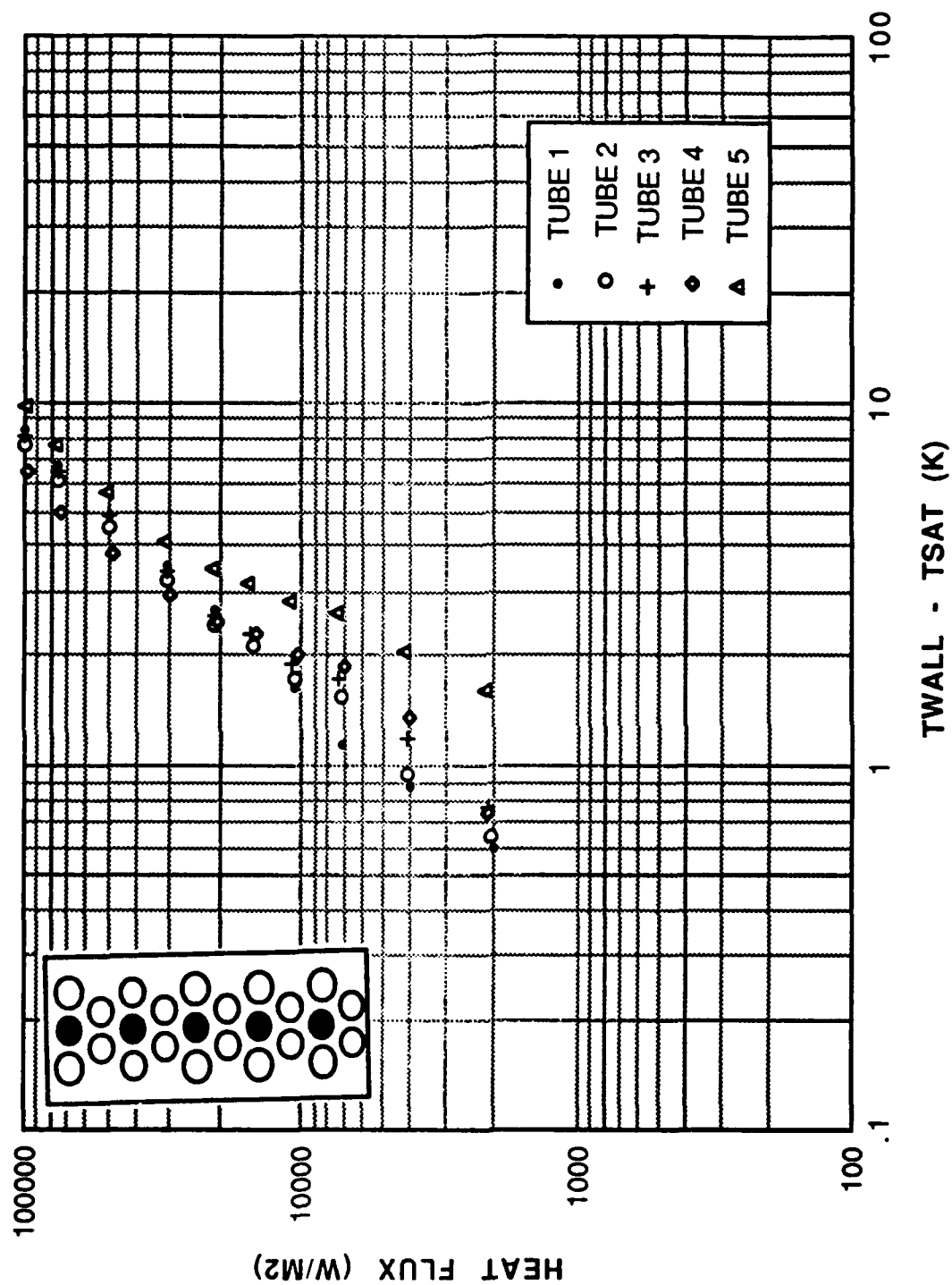


Figure 25. Performance of All Five Tubes for Decreasing Heat Flux in Pure R-114



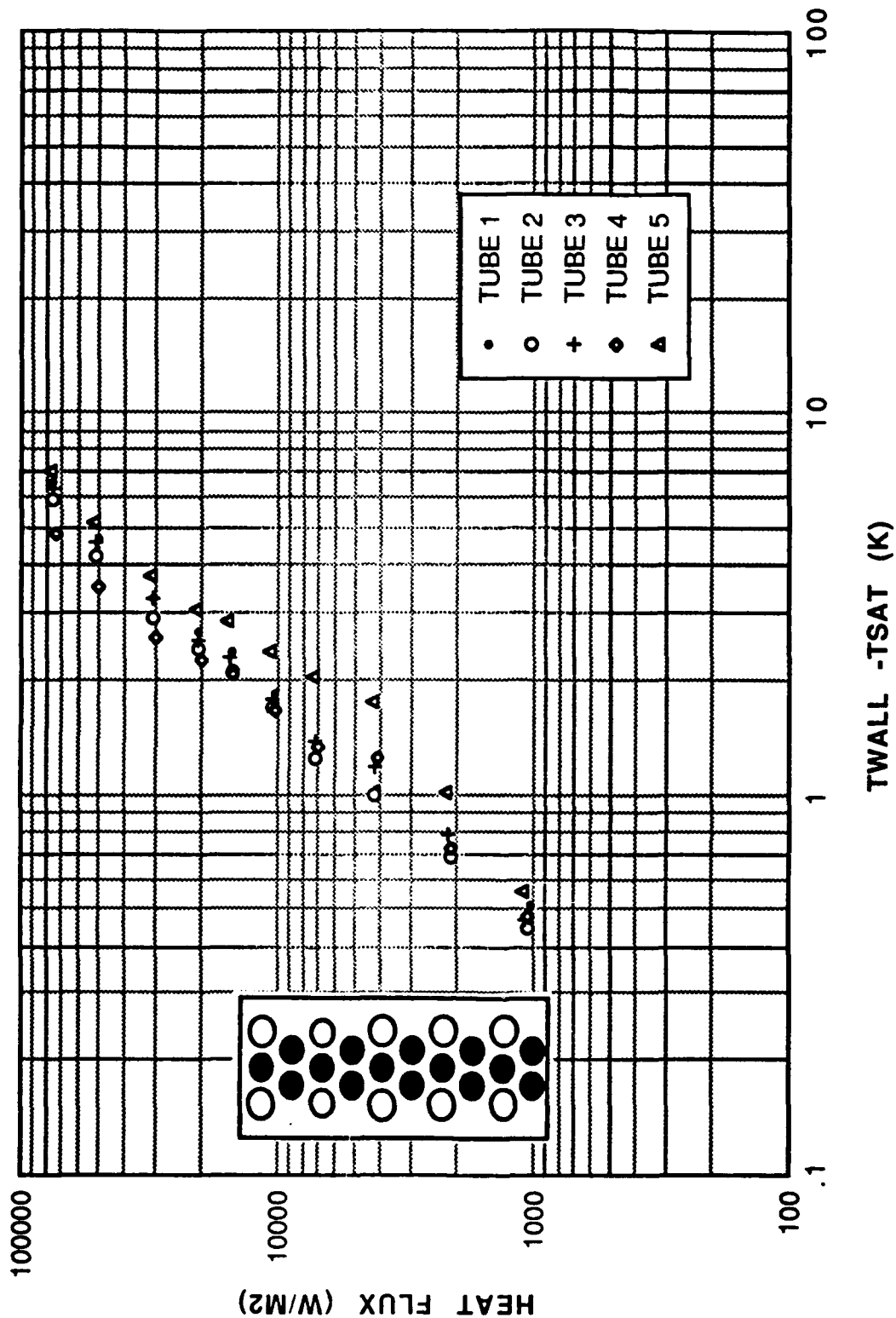


Figure 26. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in Pure R-114

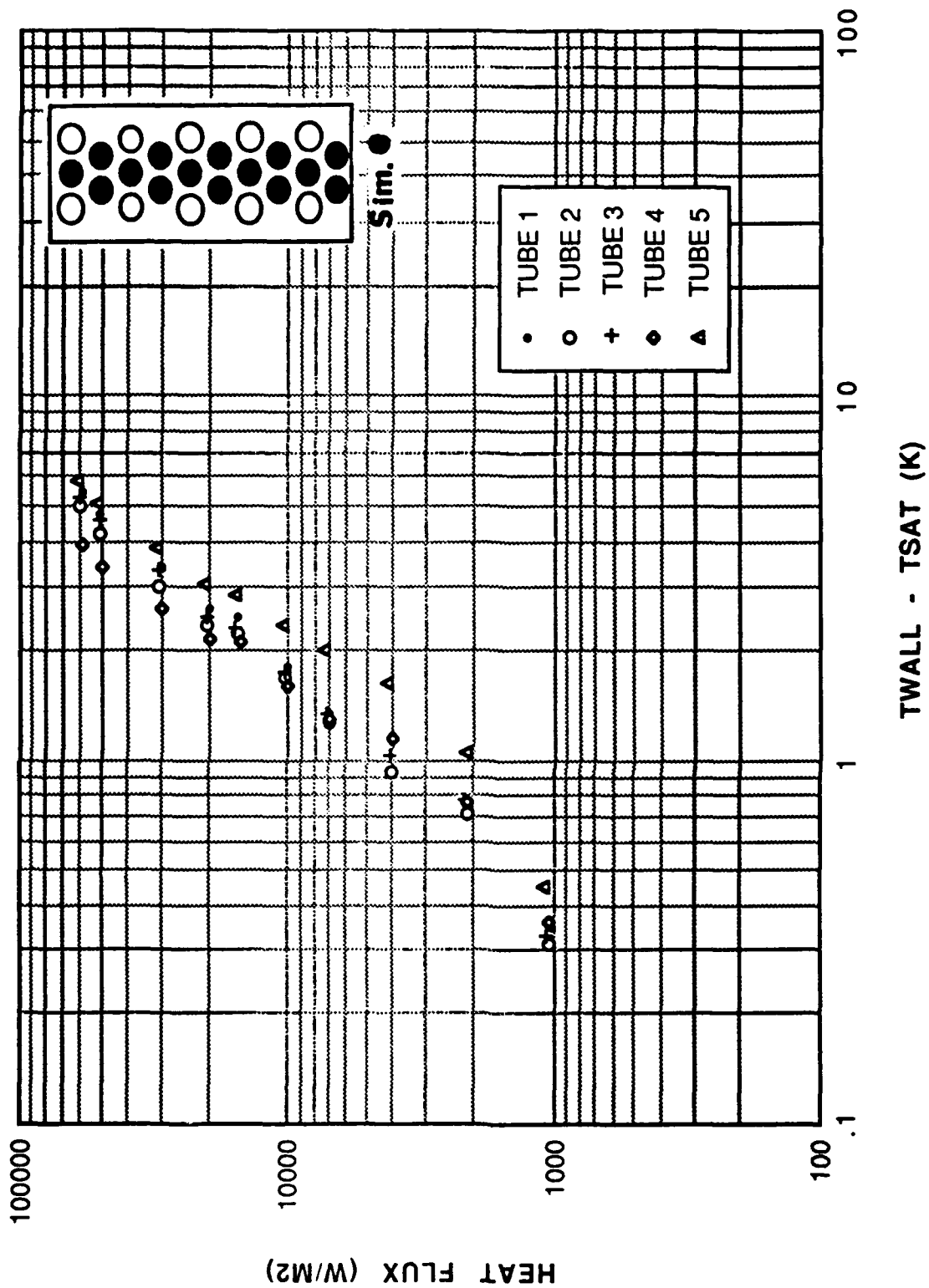


Figure 27. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in Pure R-114

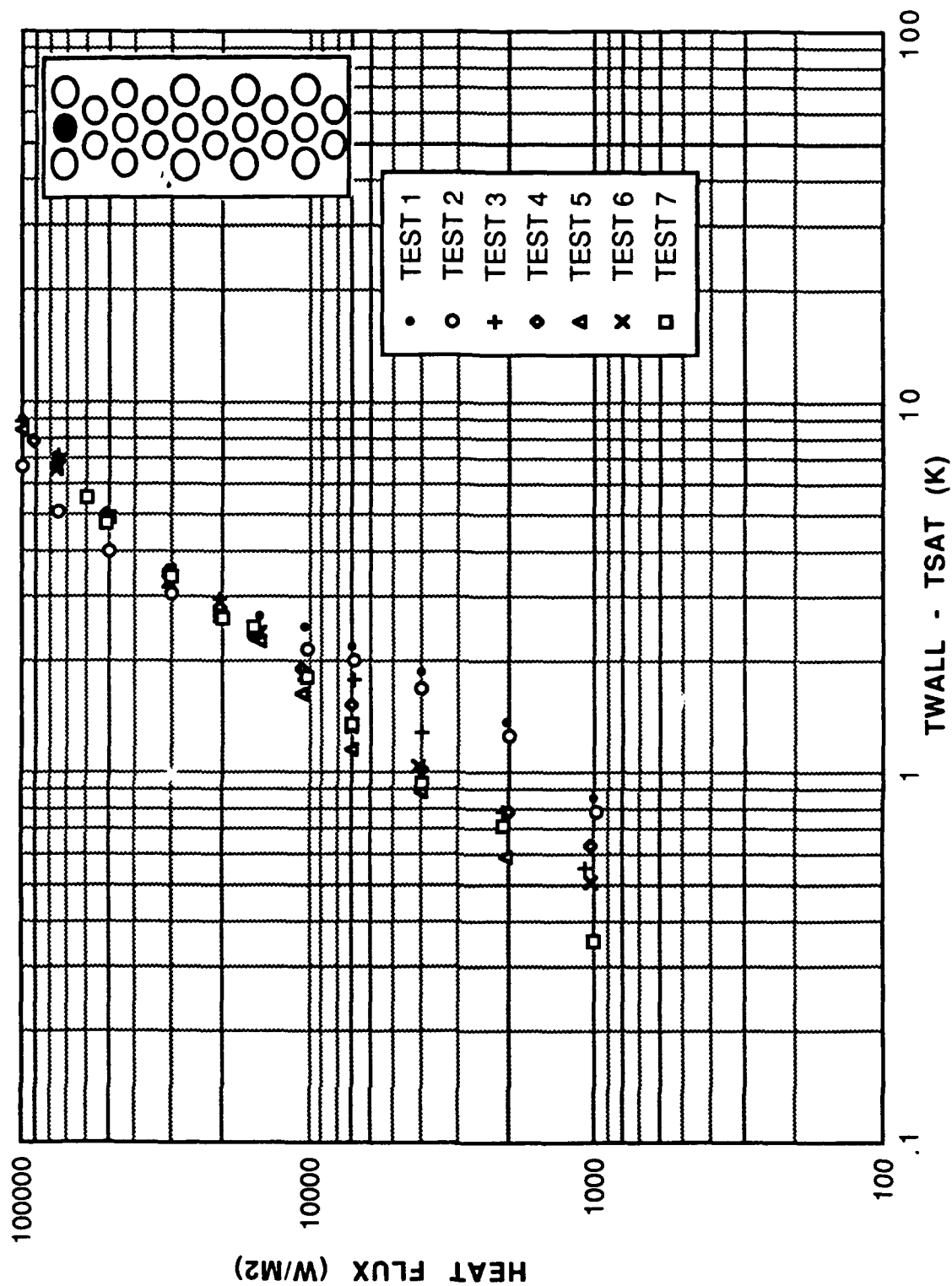


Figure 28. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in Pure R-114

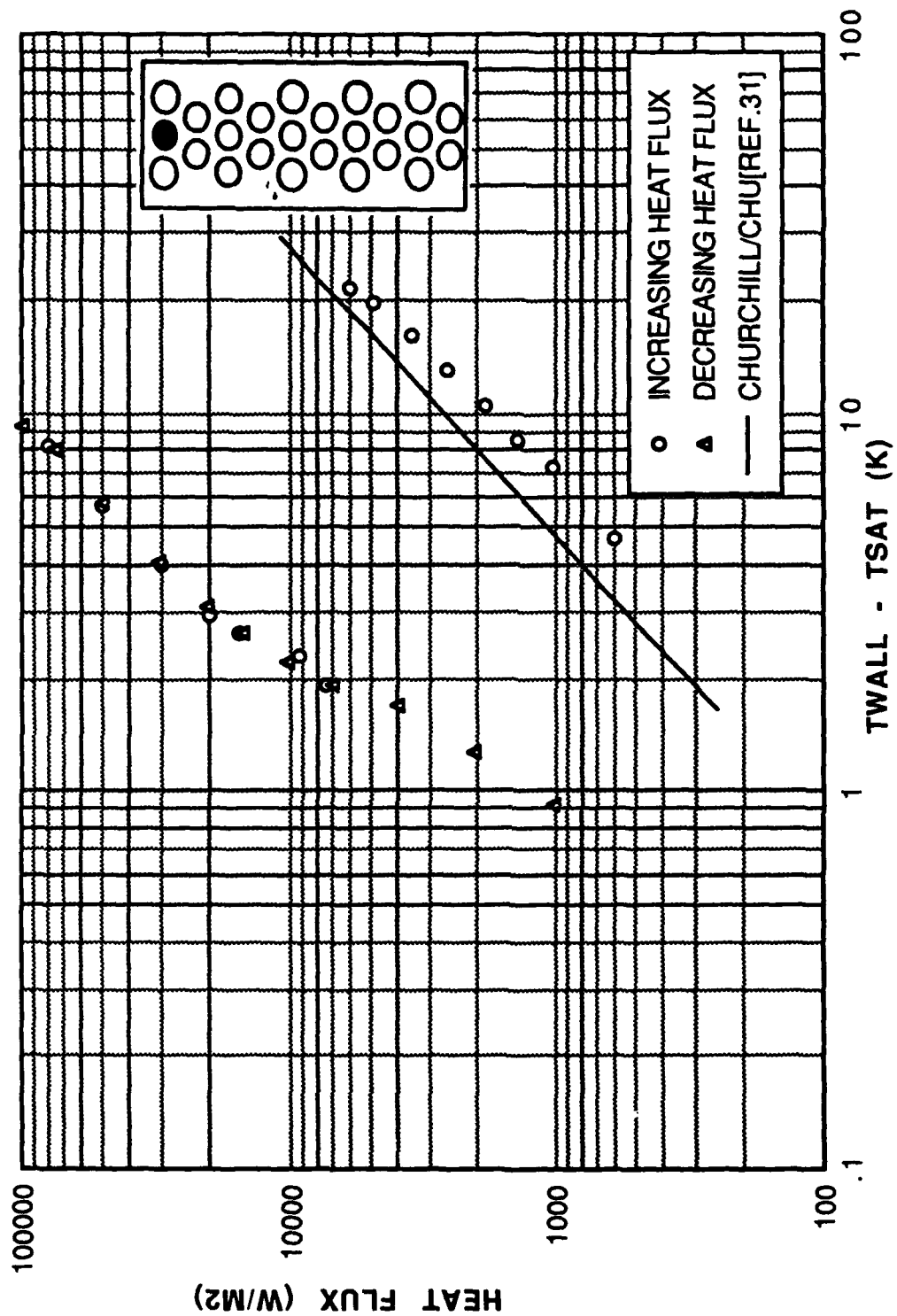


Figure 29. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 1% Oil

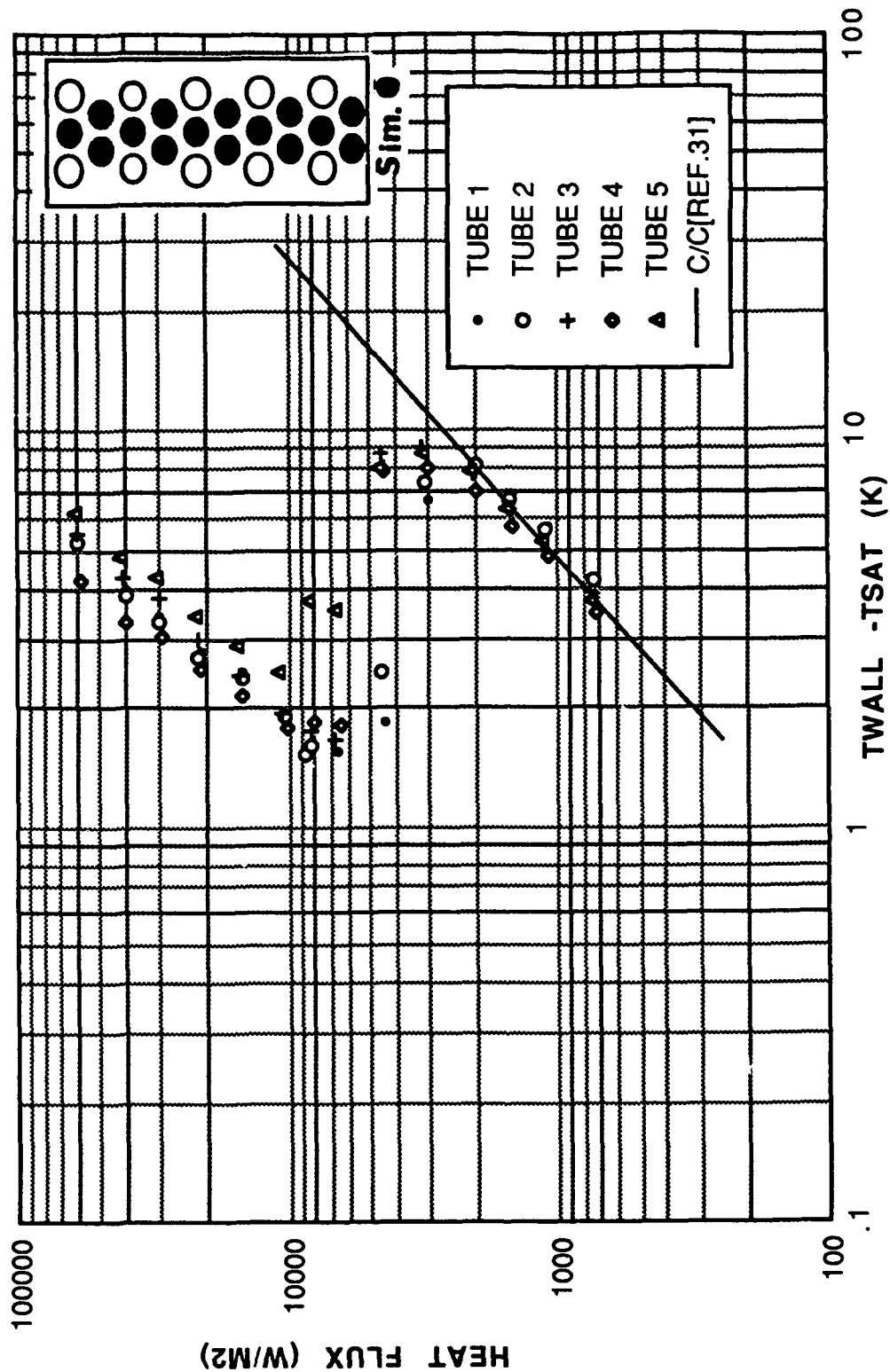


Figure 30. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 1% Oil

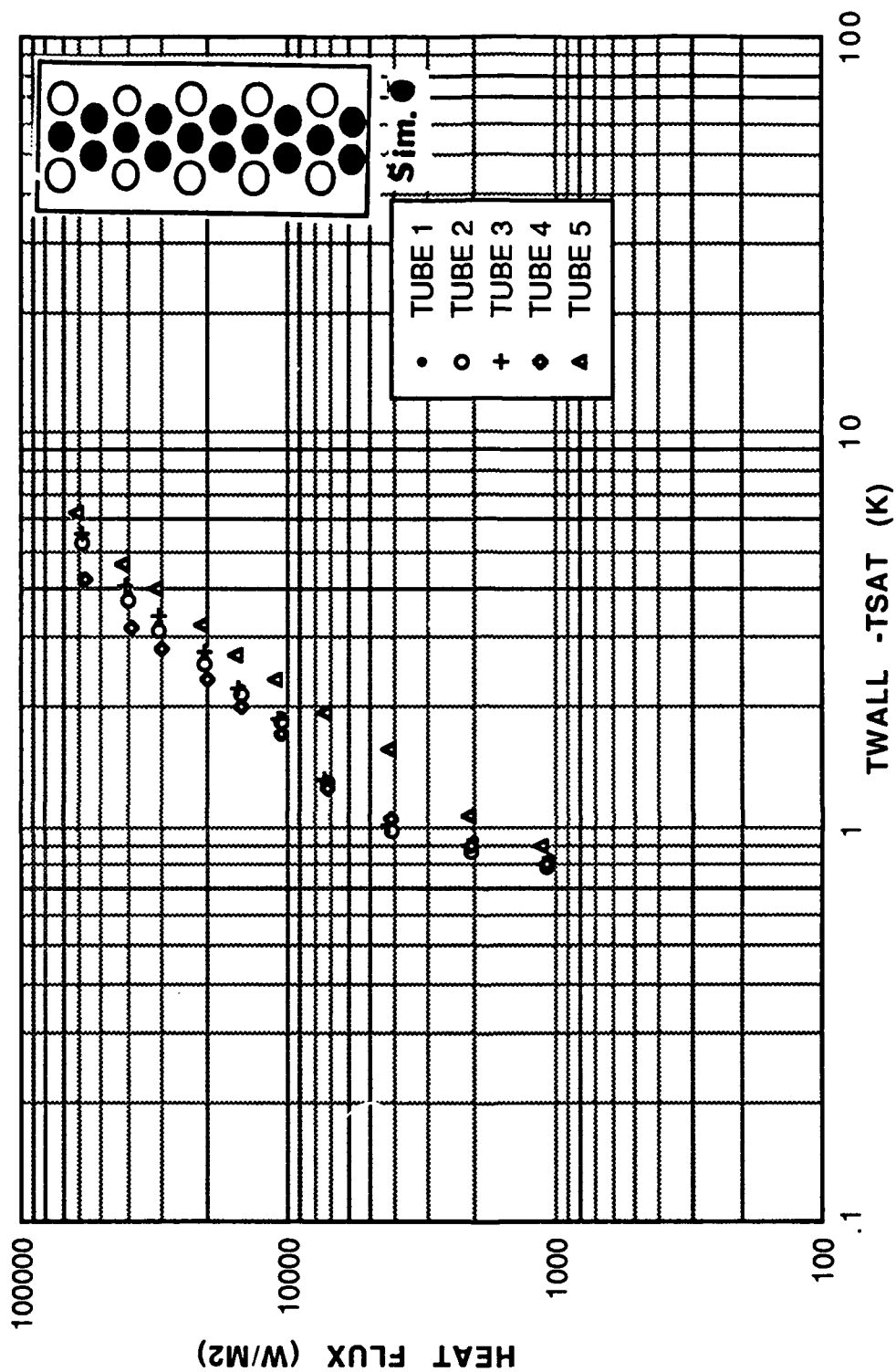


Figure 31. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 1% Oil

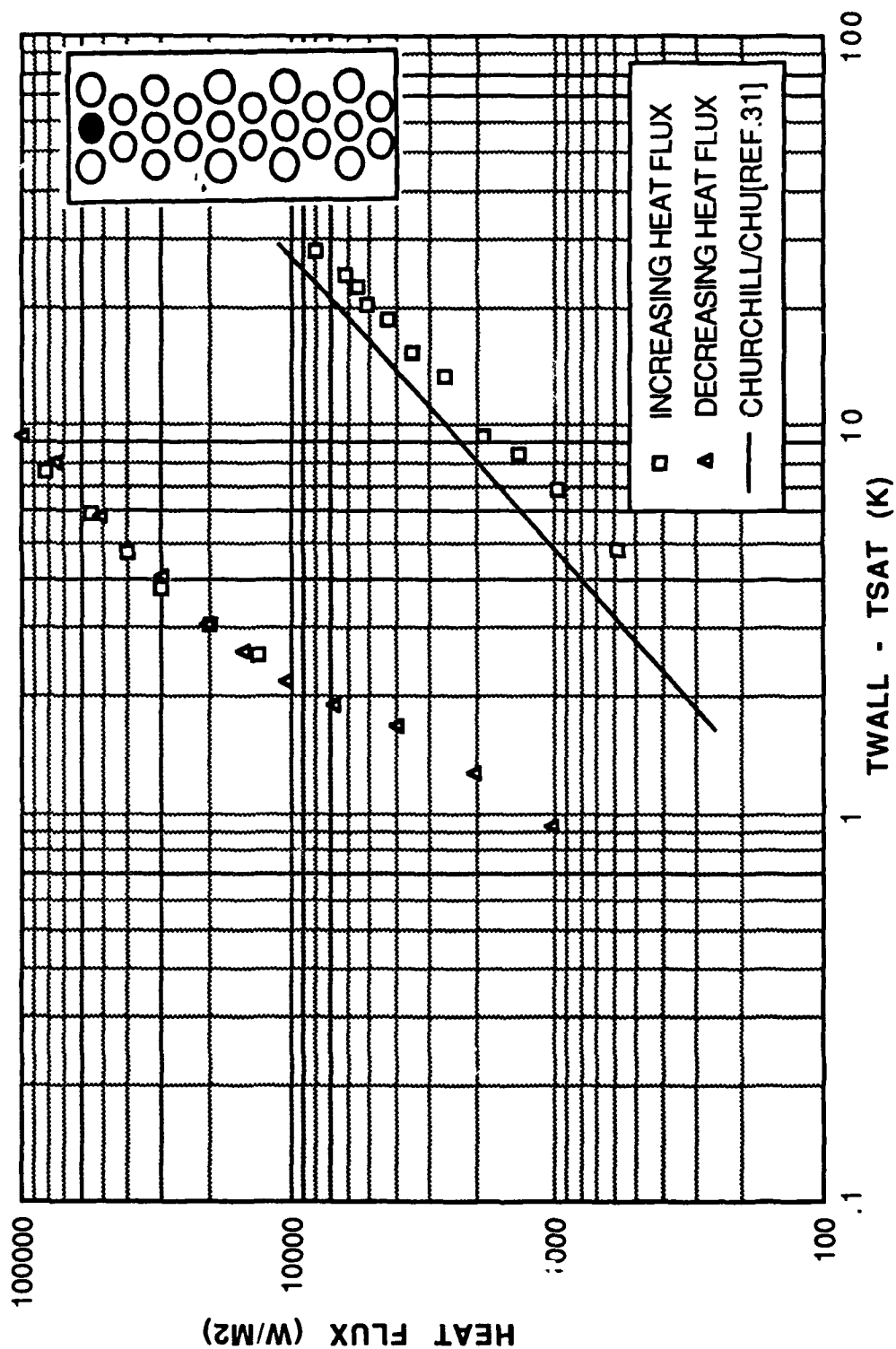


Figure 32. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 2% Oil

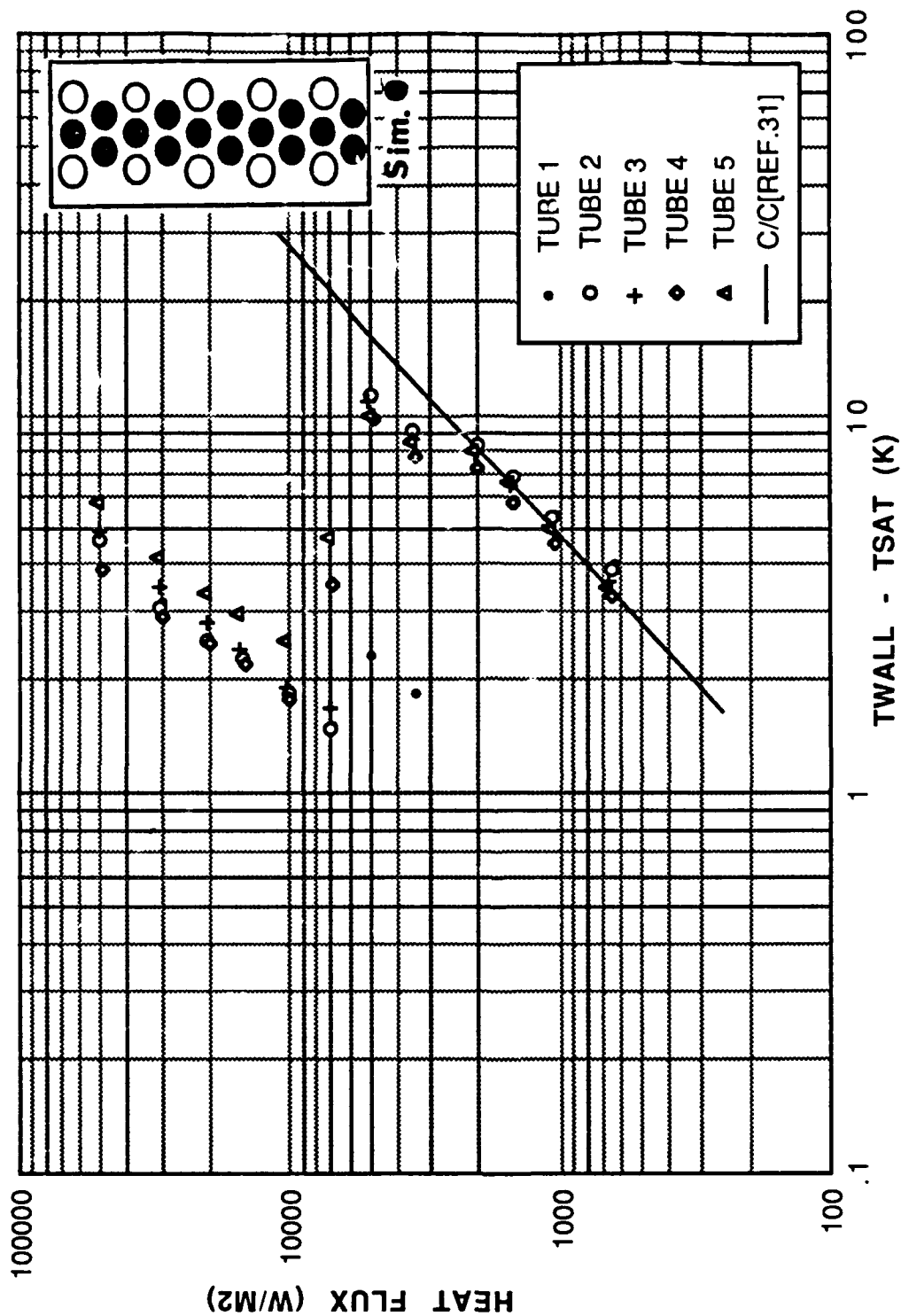


Figure 33. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 2% Oil



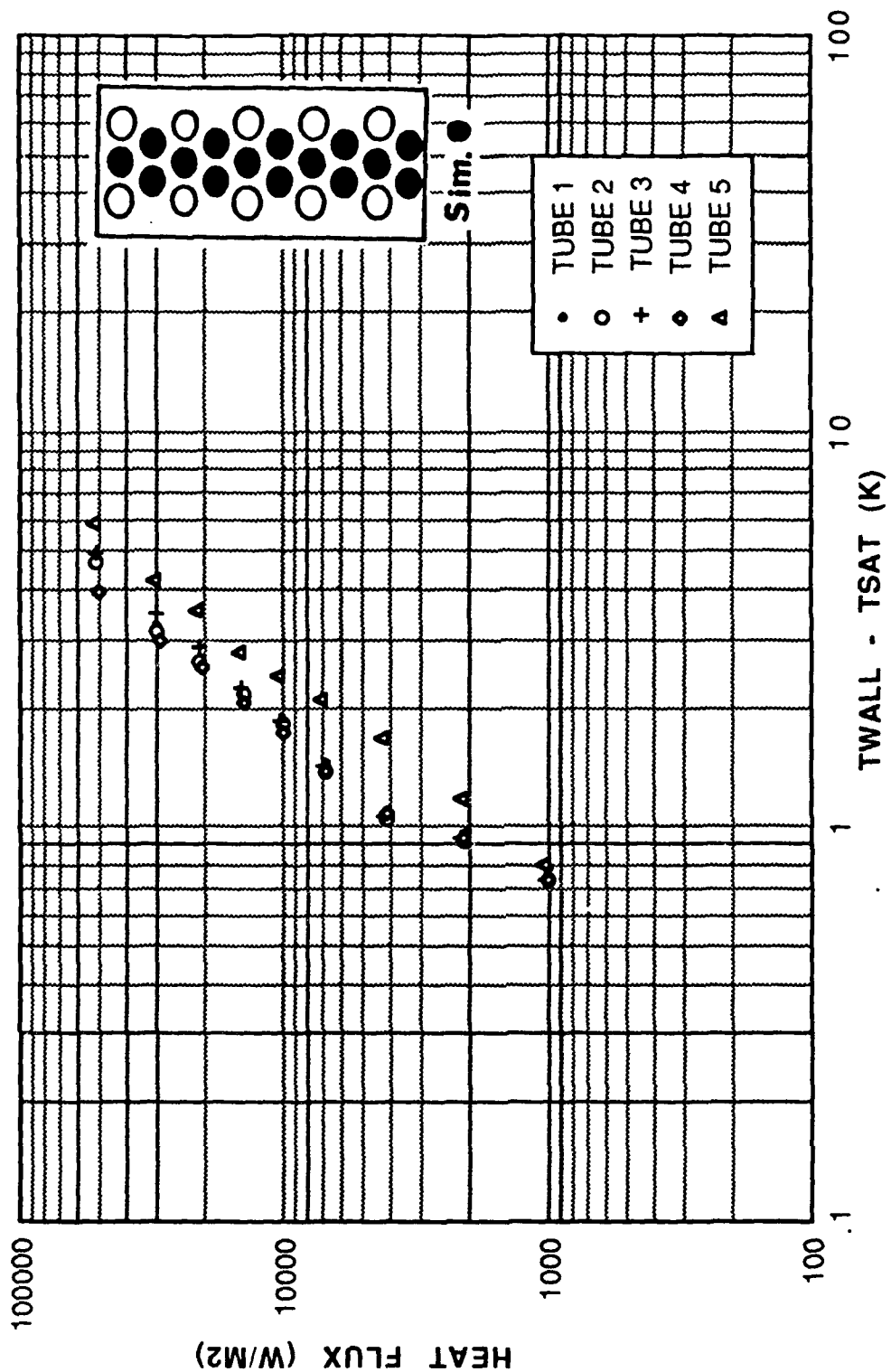


Figure 34. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 2% Oil

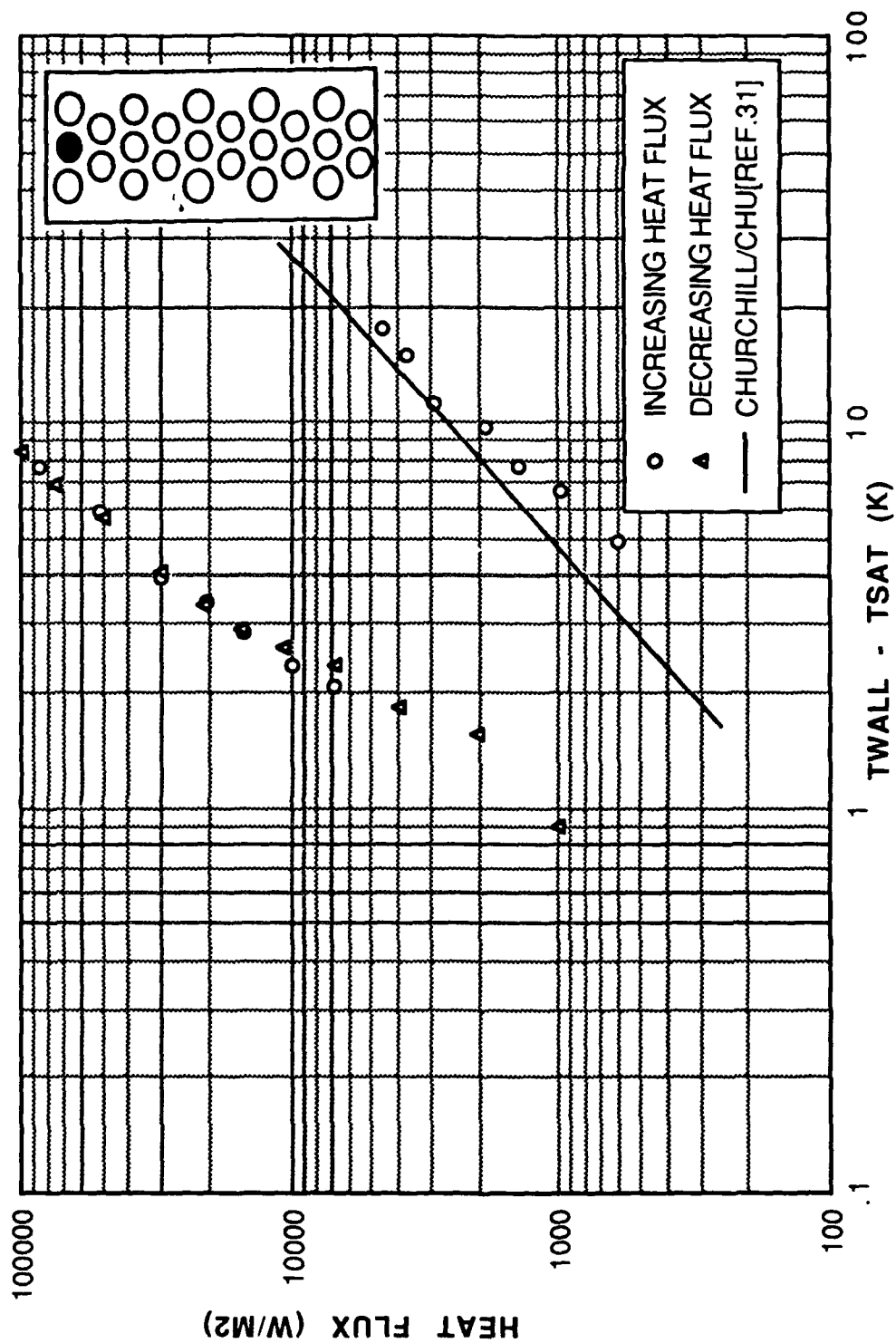


Figure 35. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 3% Oil

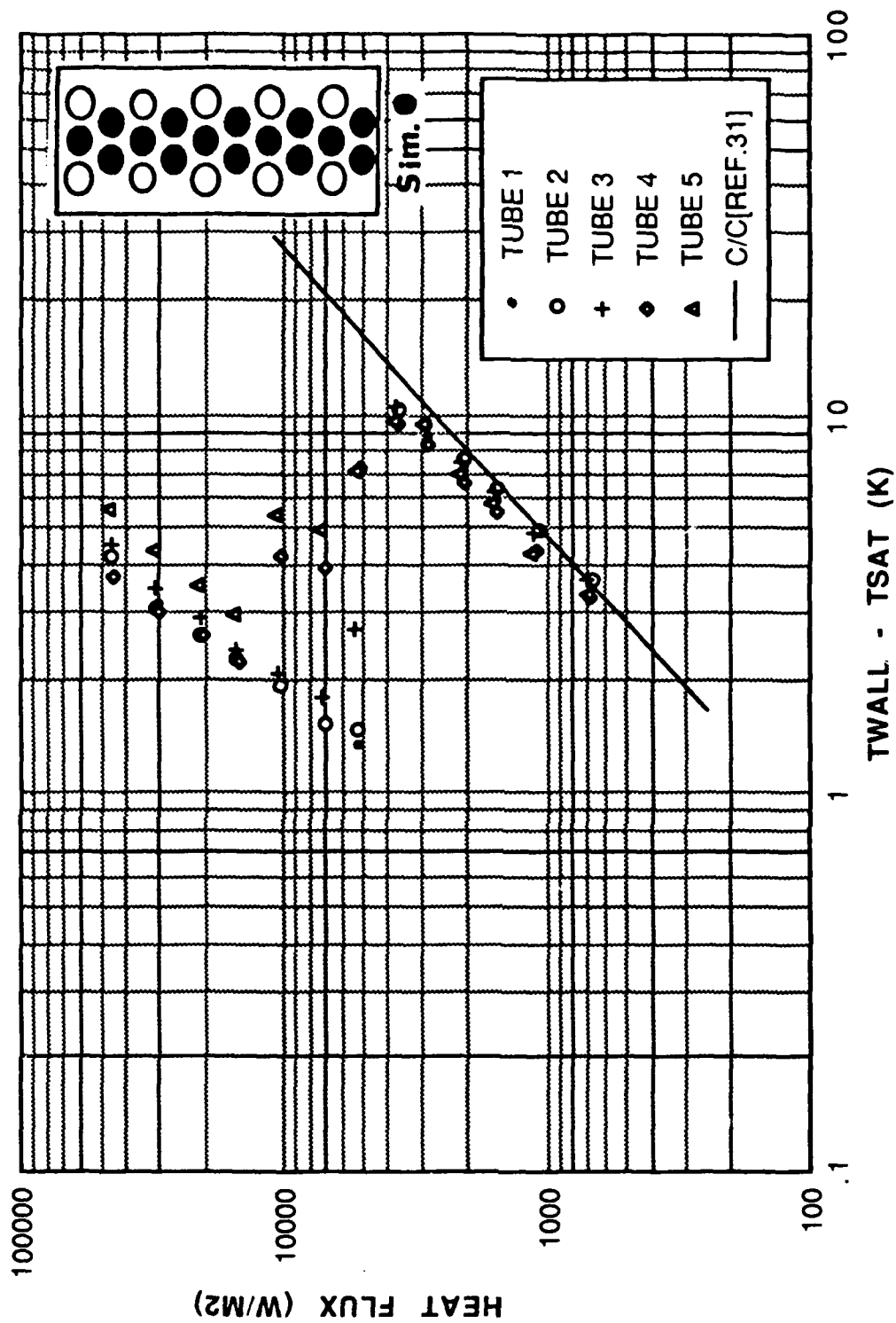


Figure 36. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 3% Oil

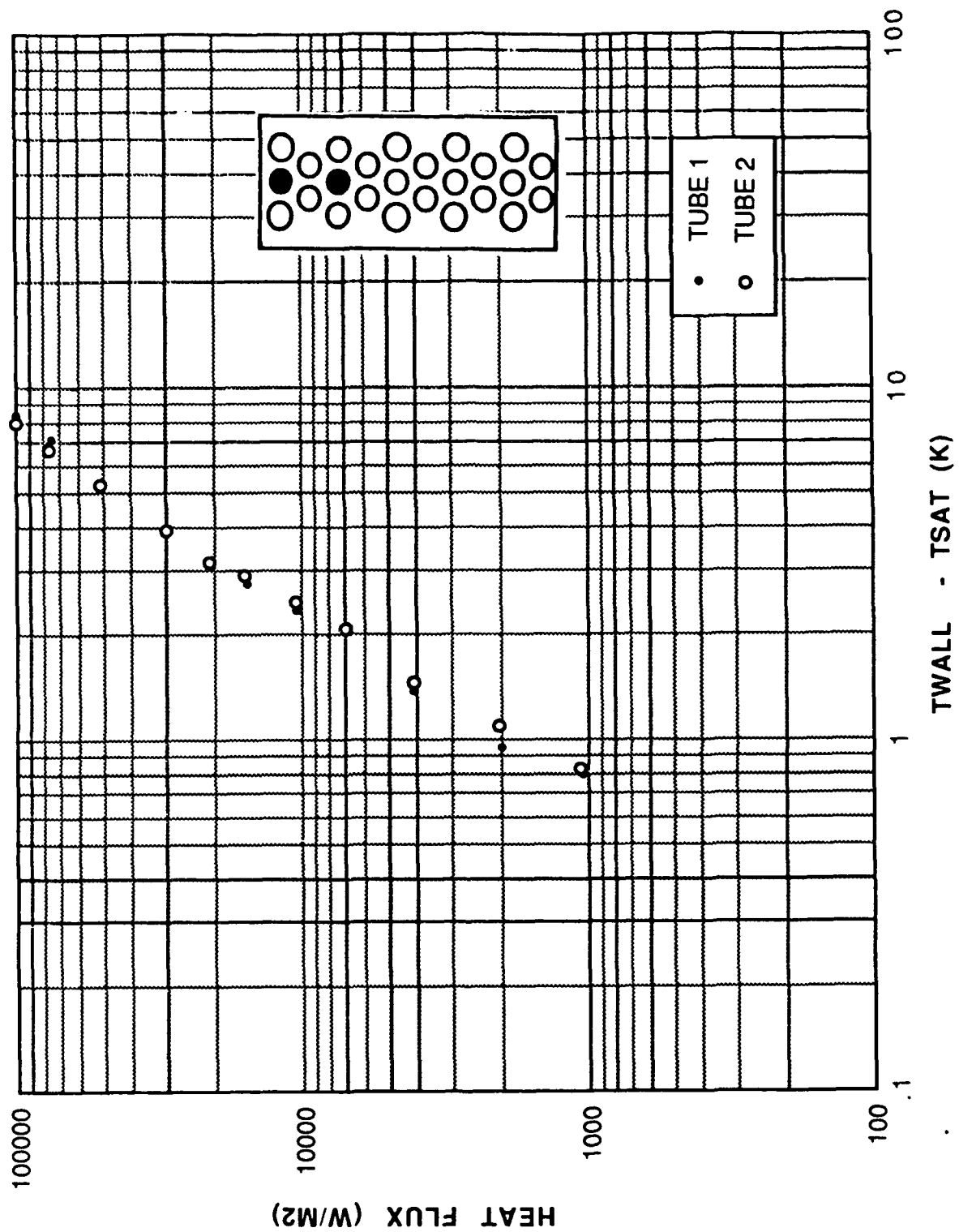


Figure 37. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 3% Oil

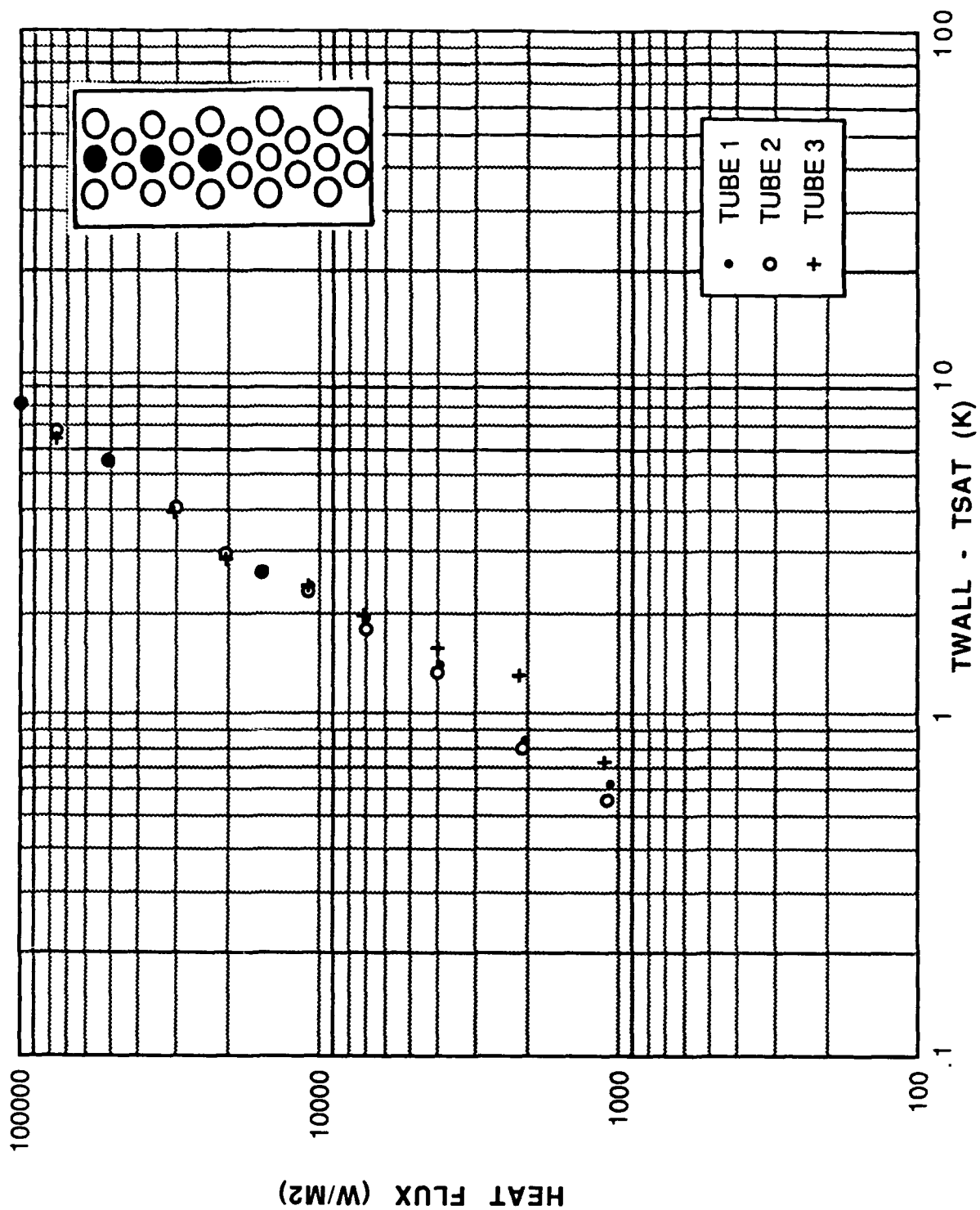


Figure 38. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 3% Oil

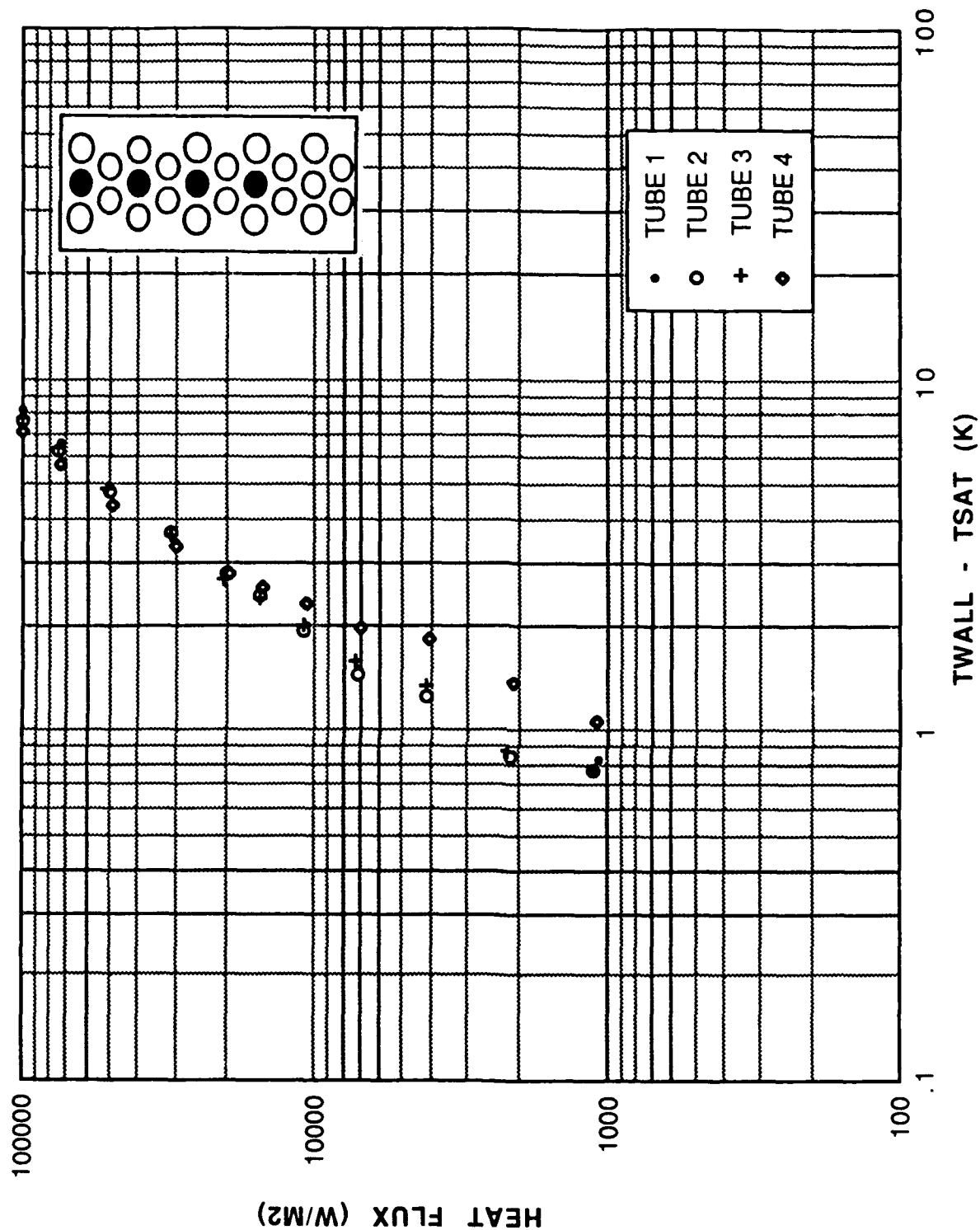


Figure 39. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 3% Oil

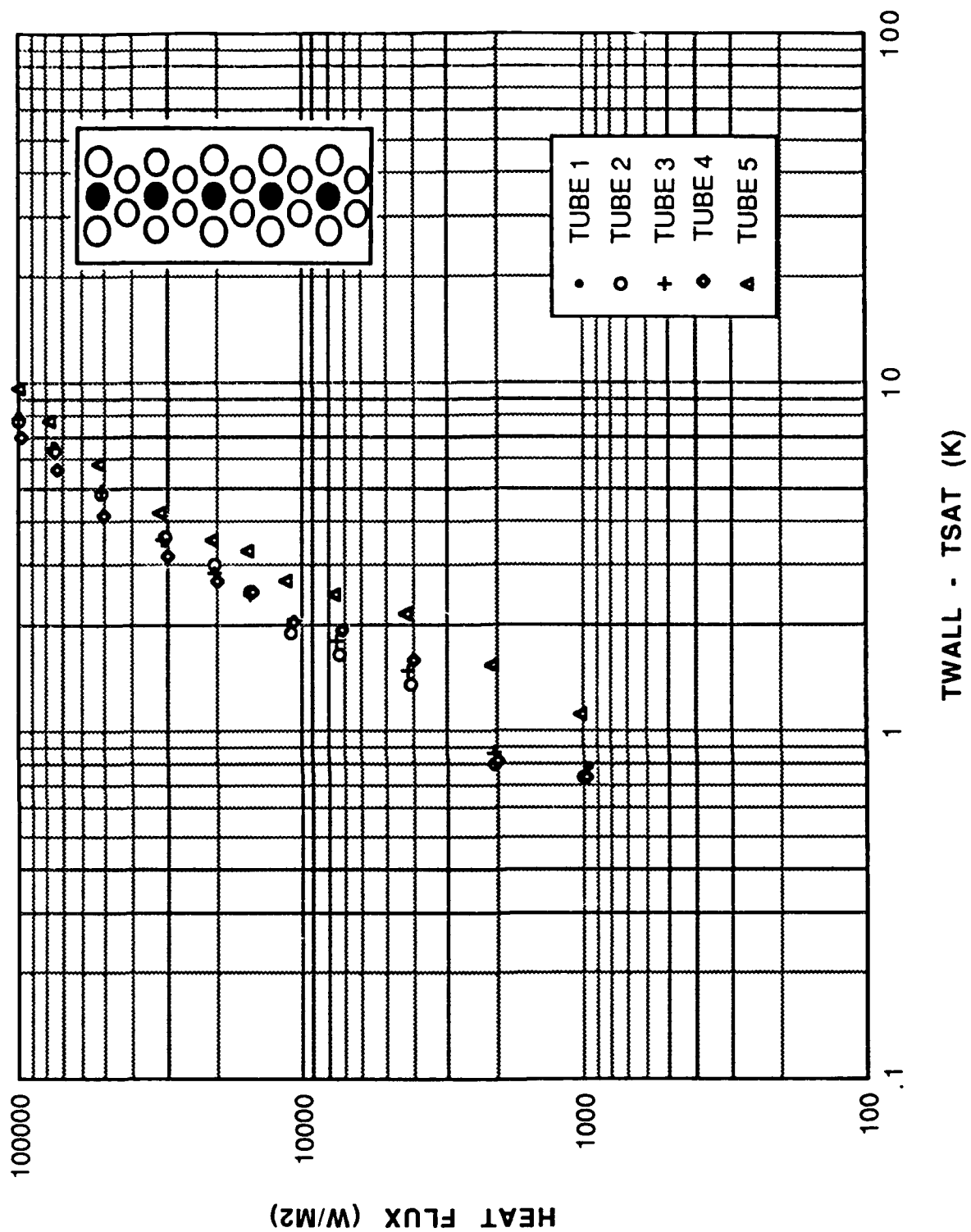


Figure 40. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 3% Oil

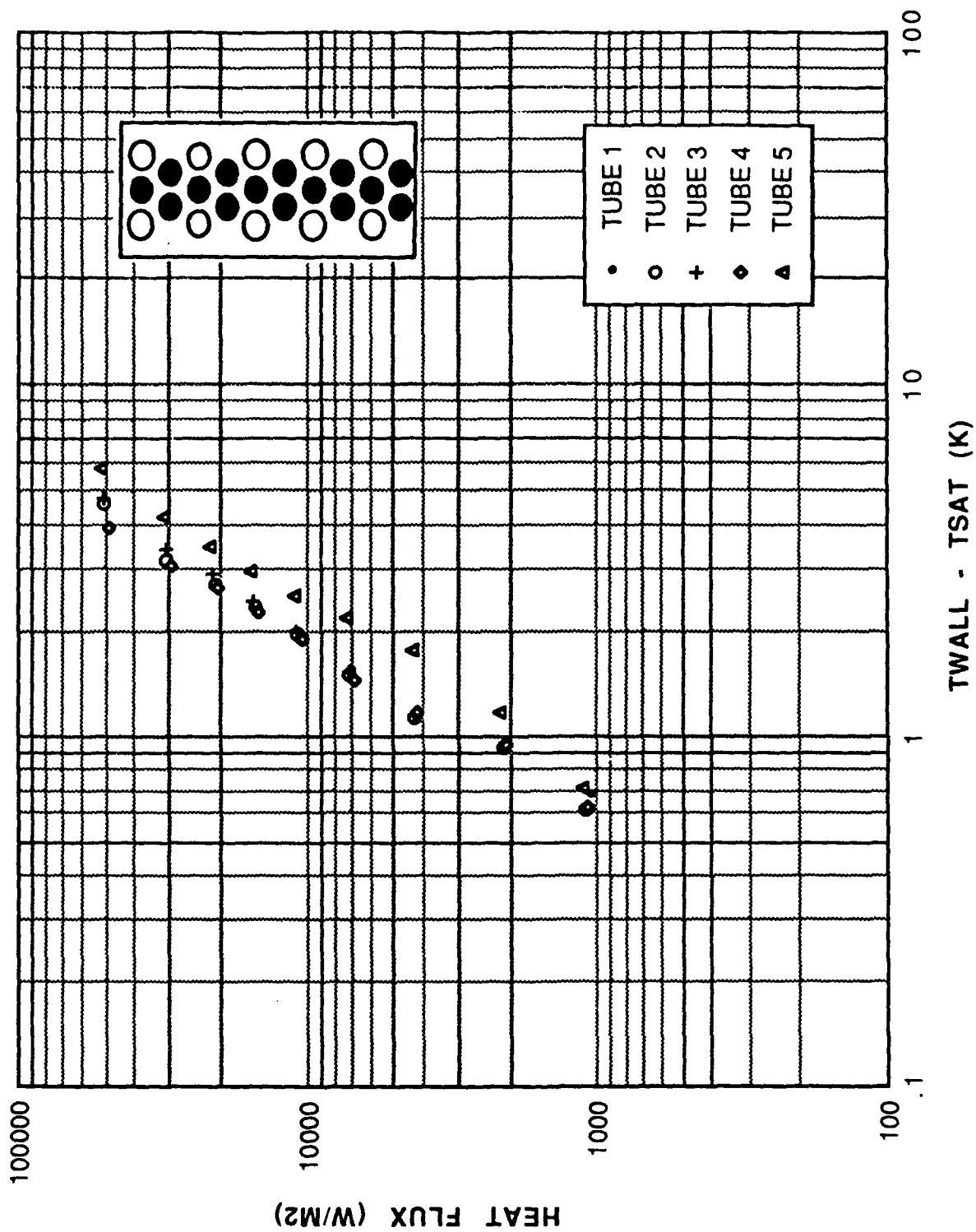


Figure 41. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 3% Oil



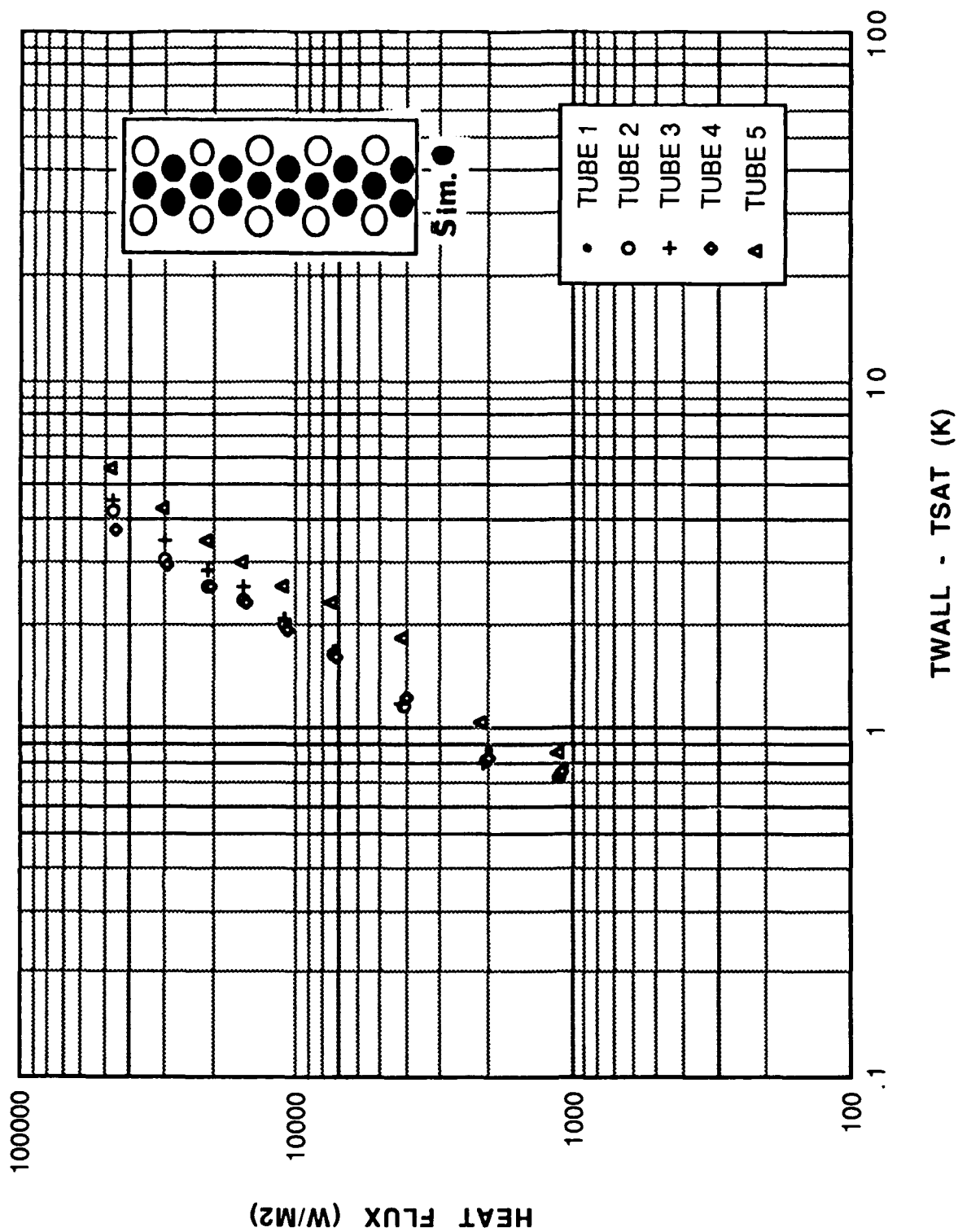


Figure 42. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 3% Oil

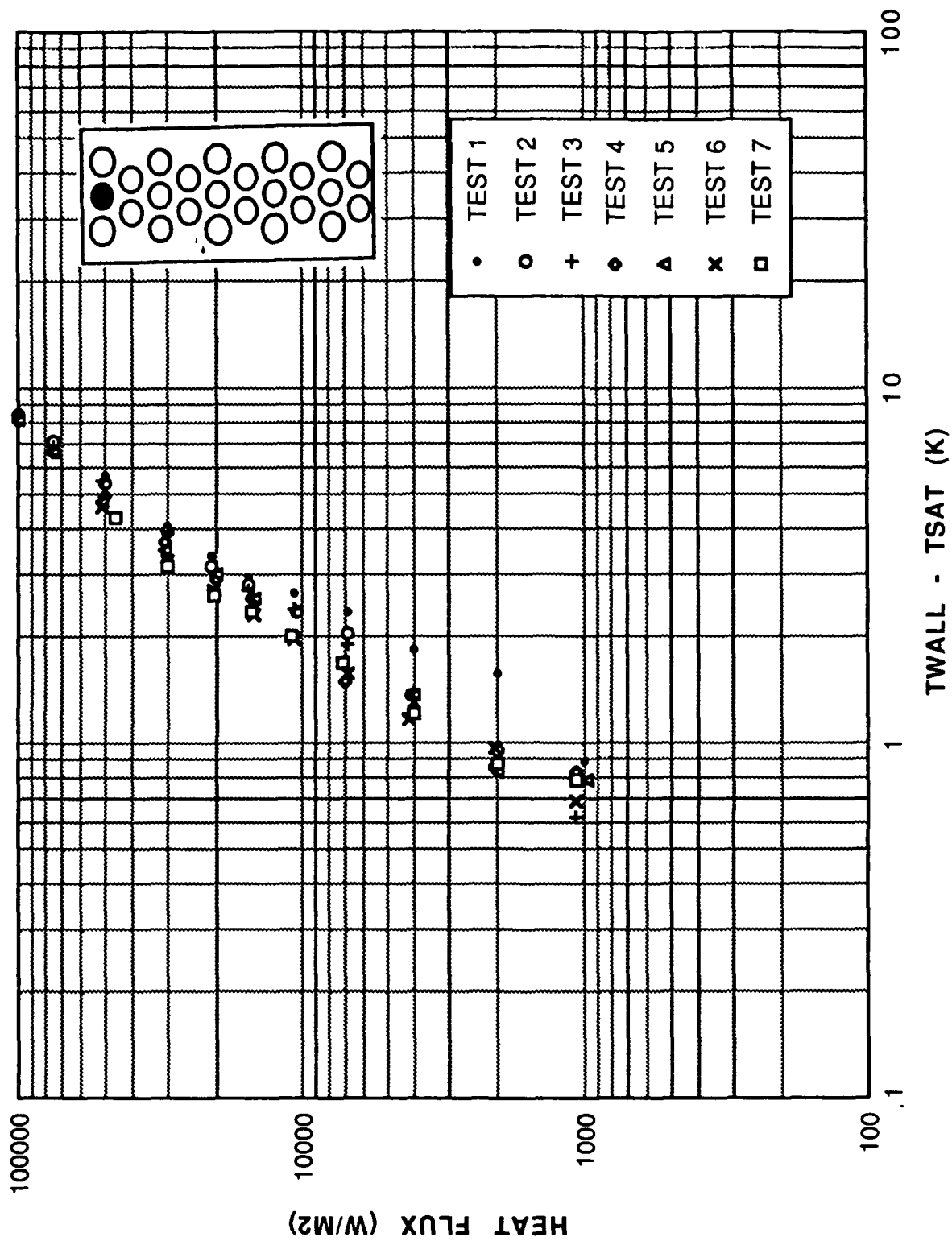


Figure 43. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in R-114 with 3% Oil

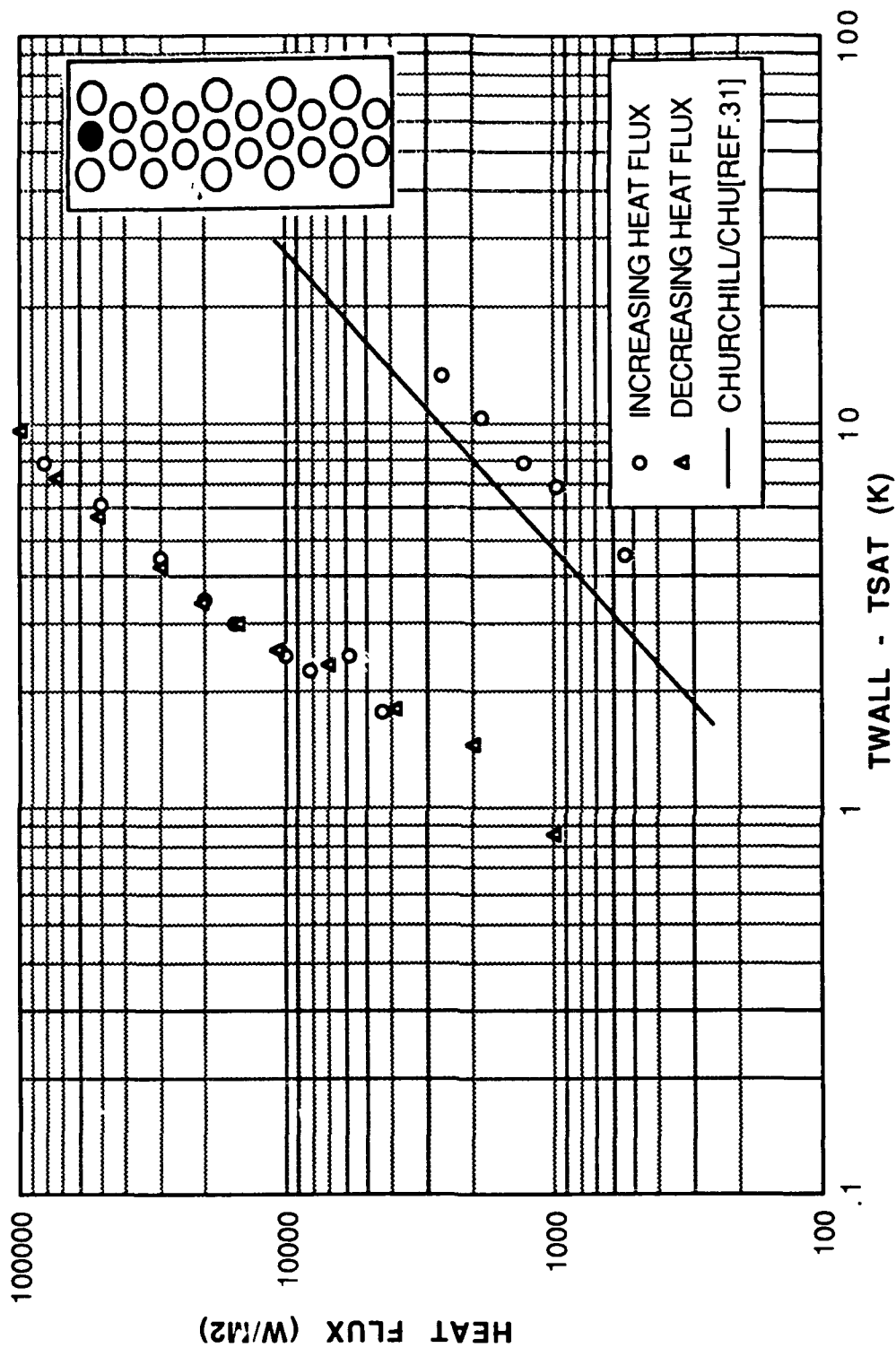


Figure 44. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 6% Oil

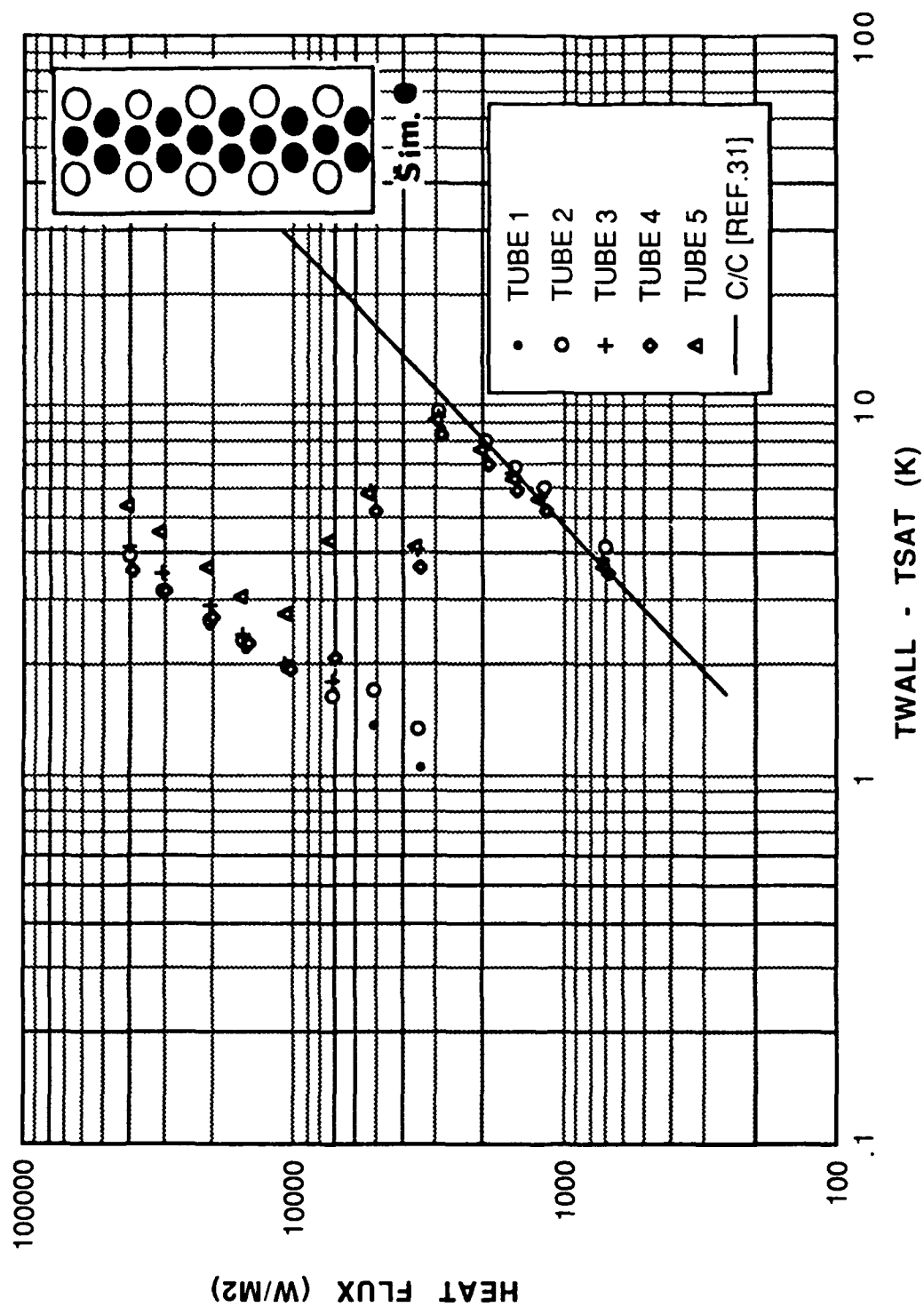


Figure 45. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 6% Oil

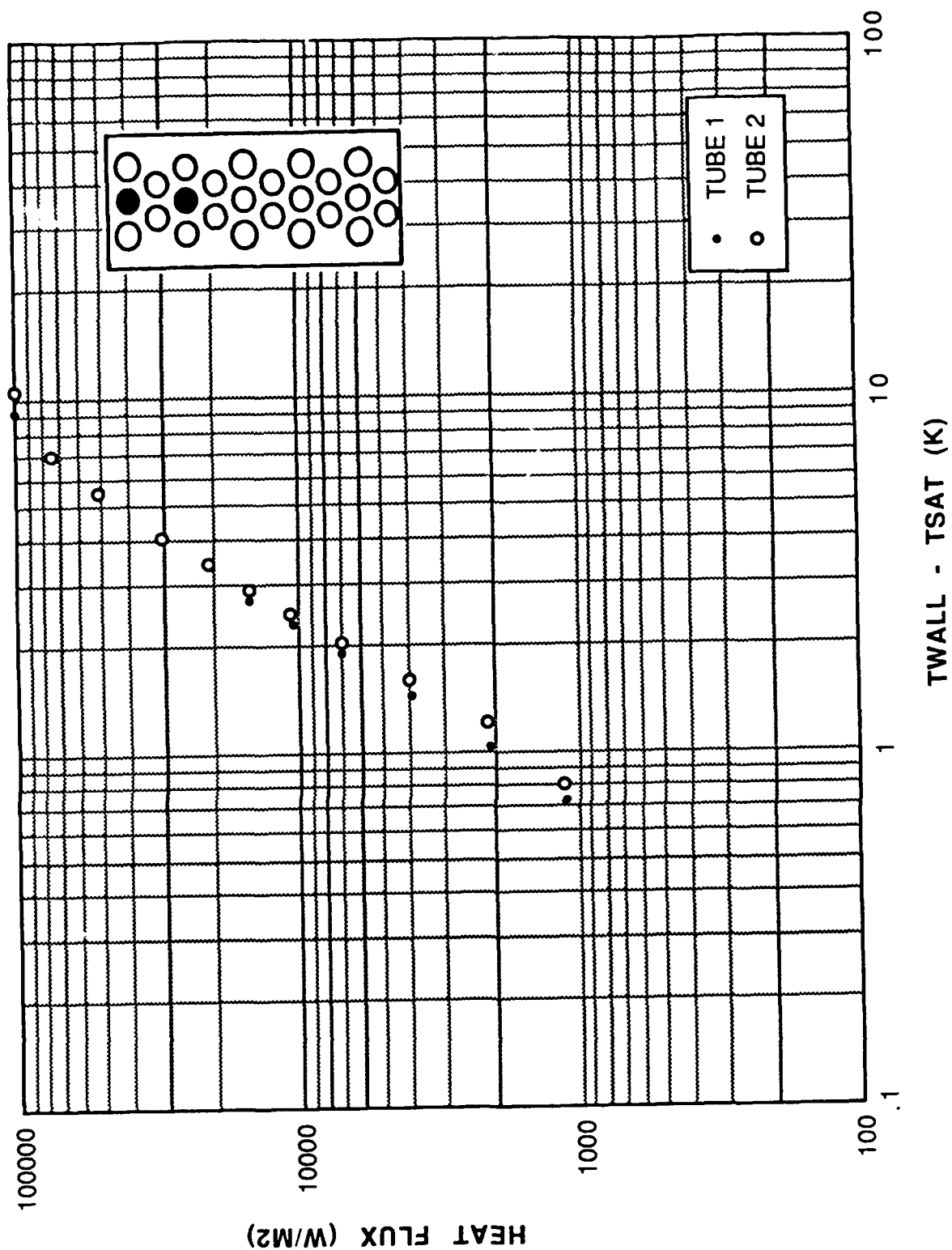


Figure 46. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 6% Oil

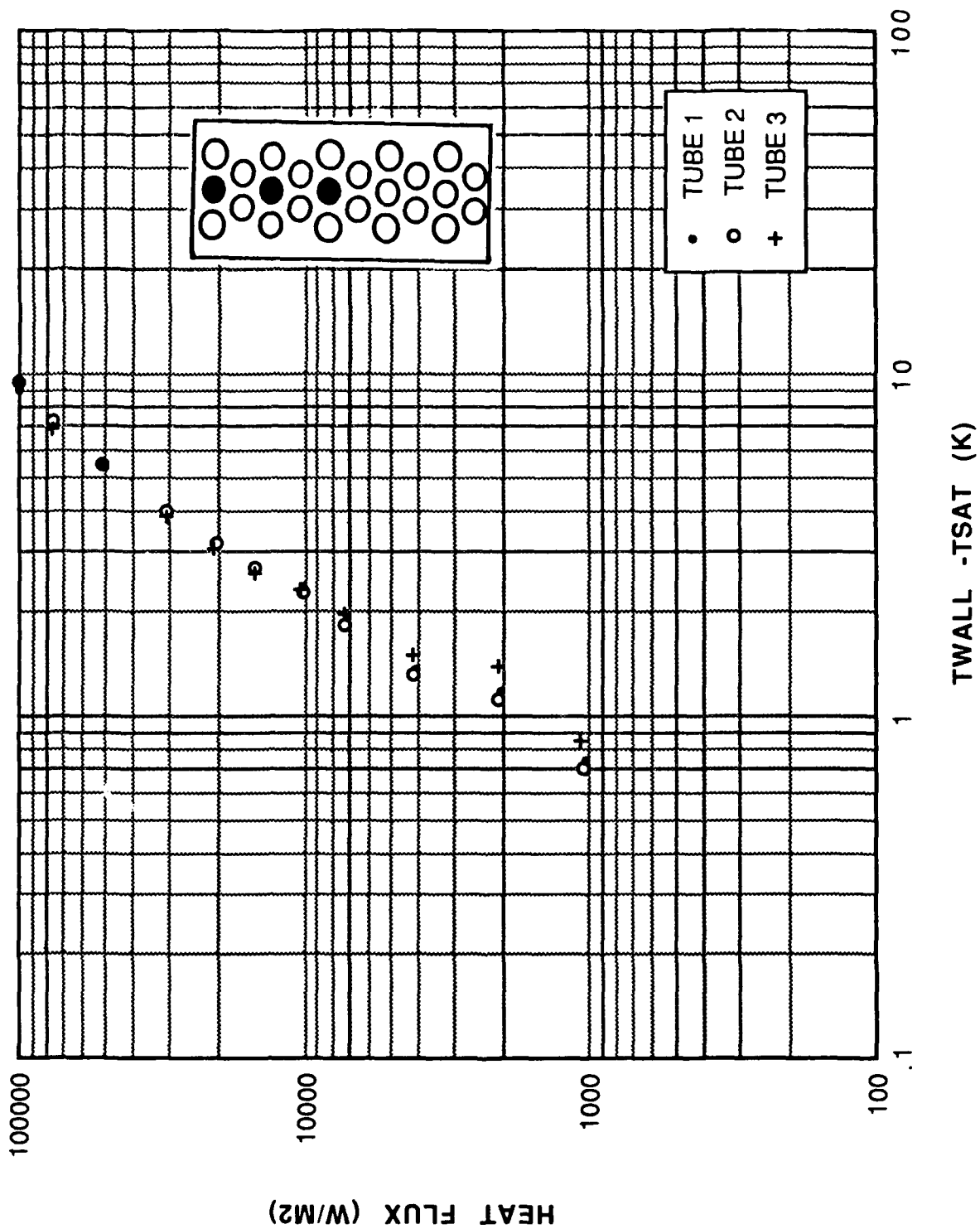


Figure 47. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 6% Oil

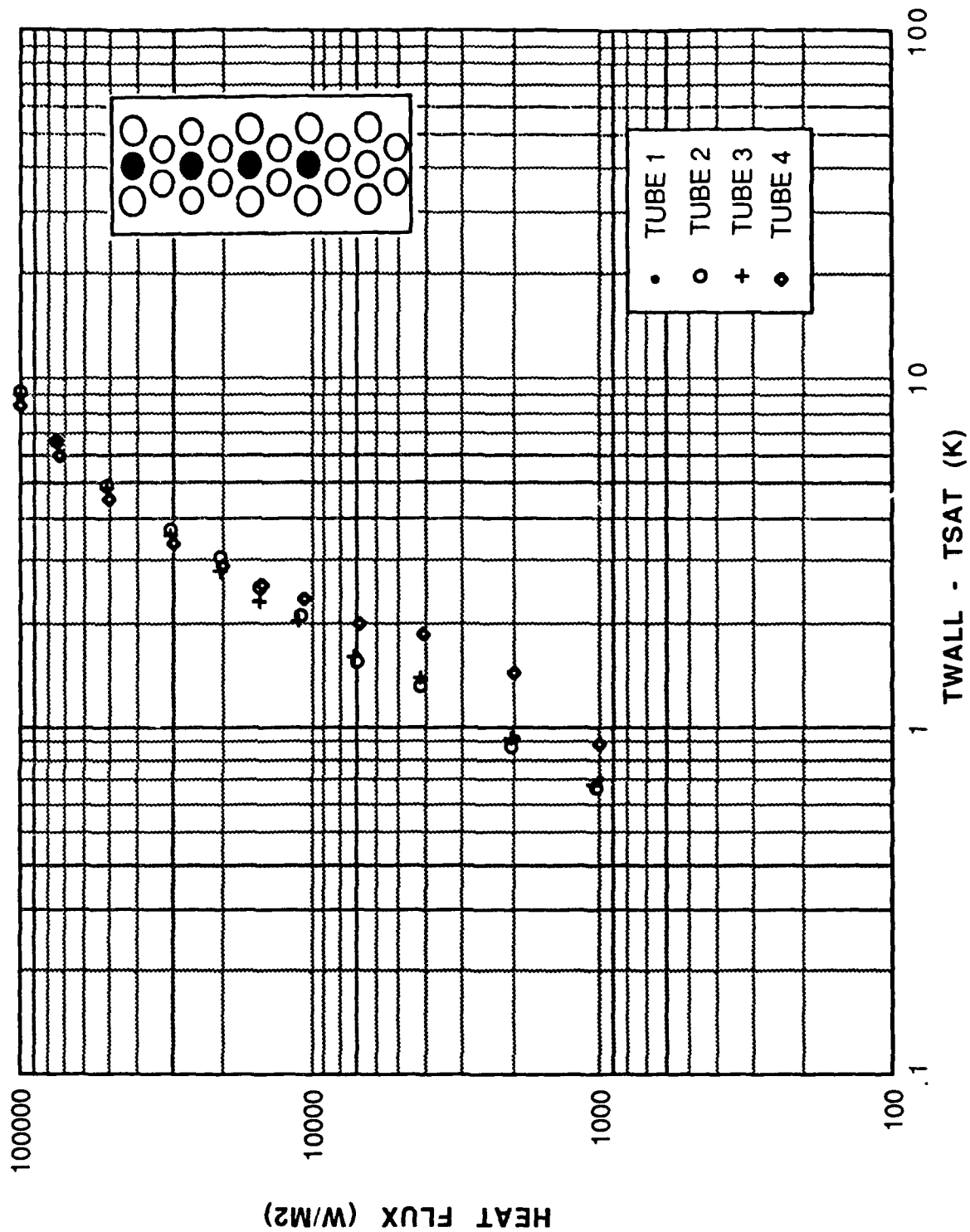


Figure 48. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 6% Oil

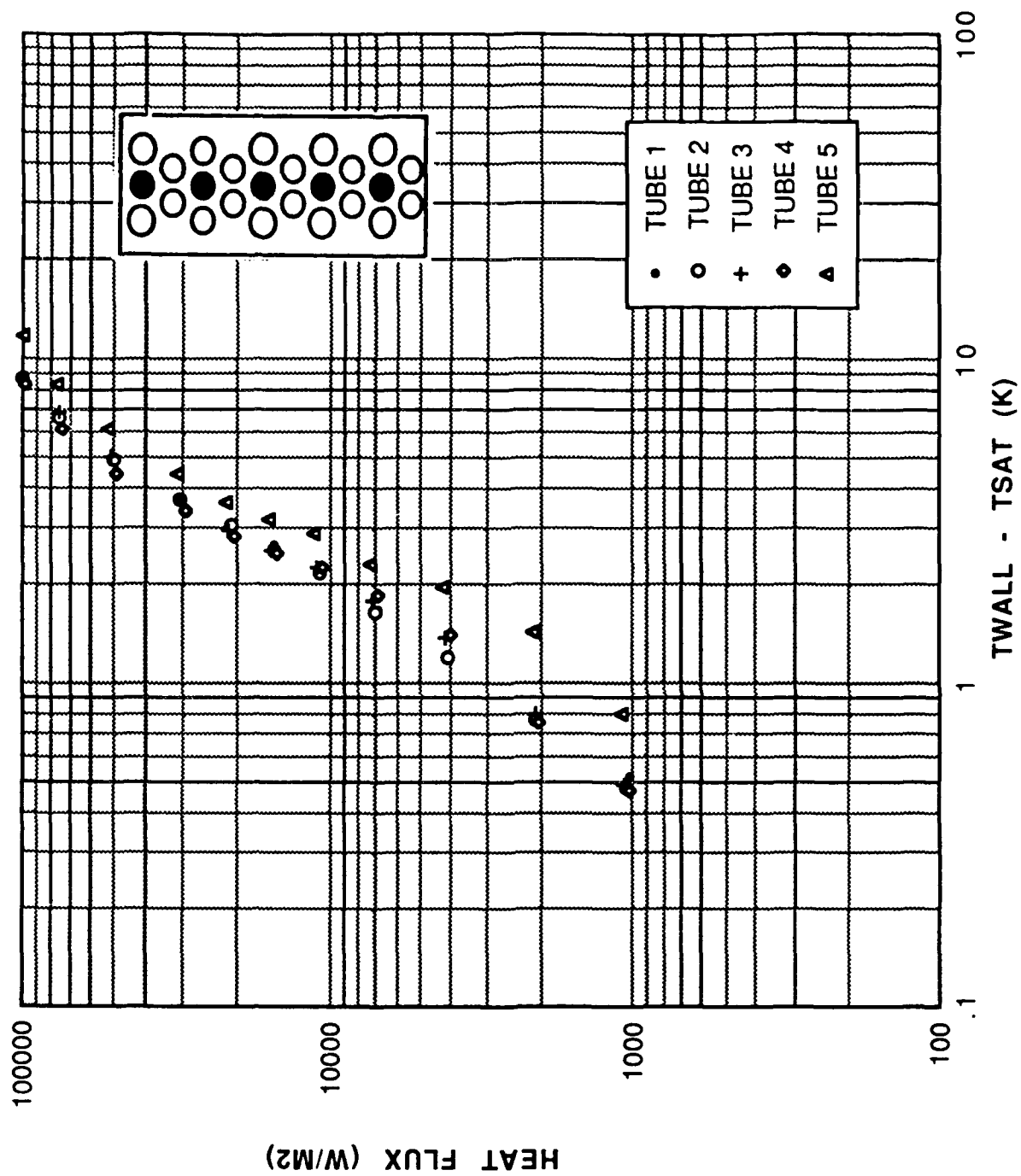


Figure 49. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 6% Oil



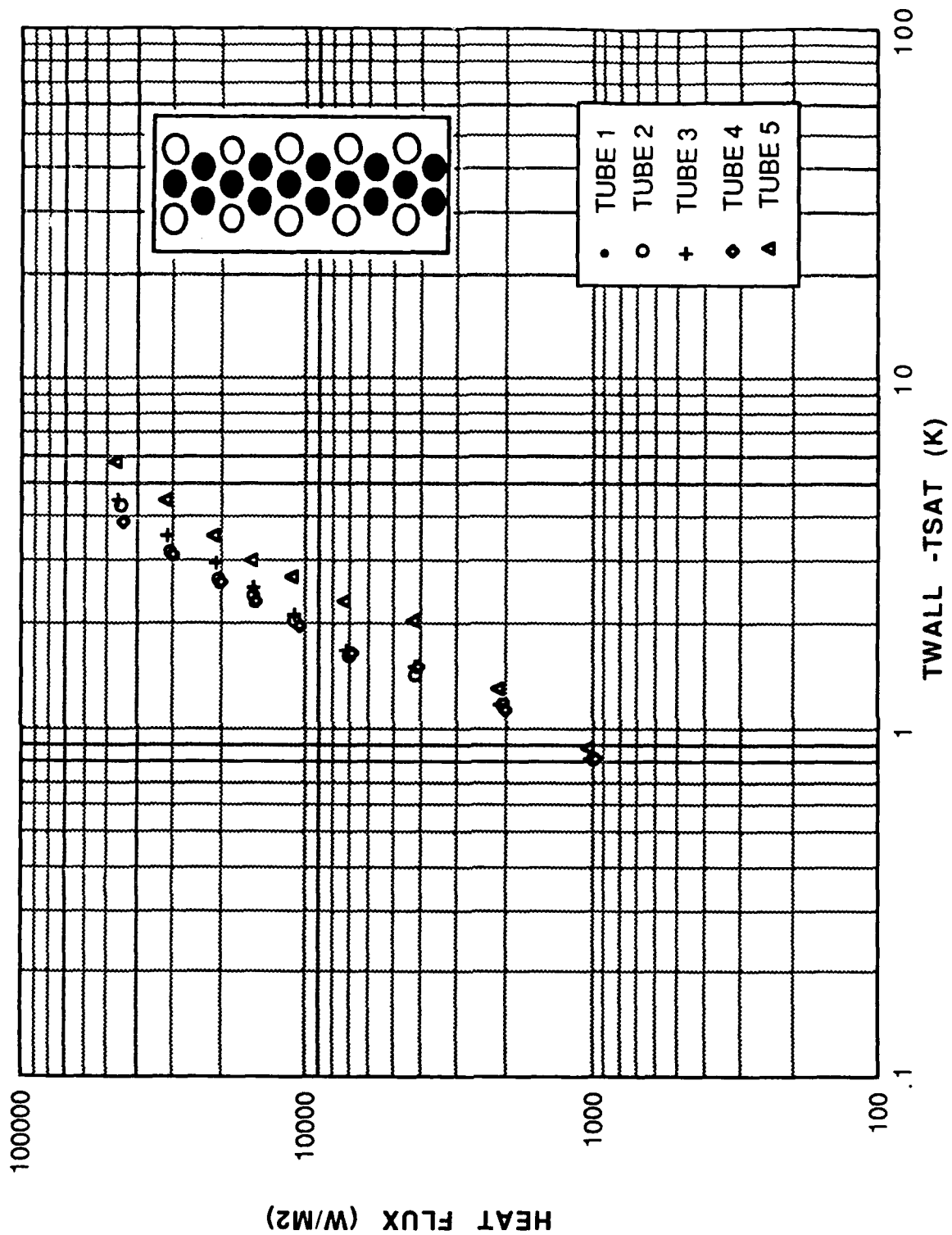


Figure 50. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 6% Oil

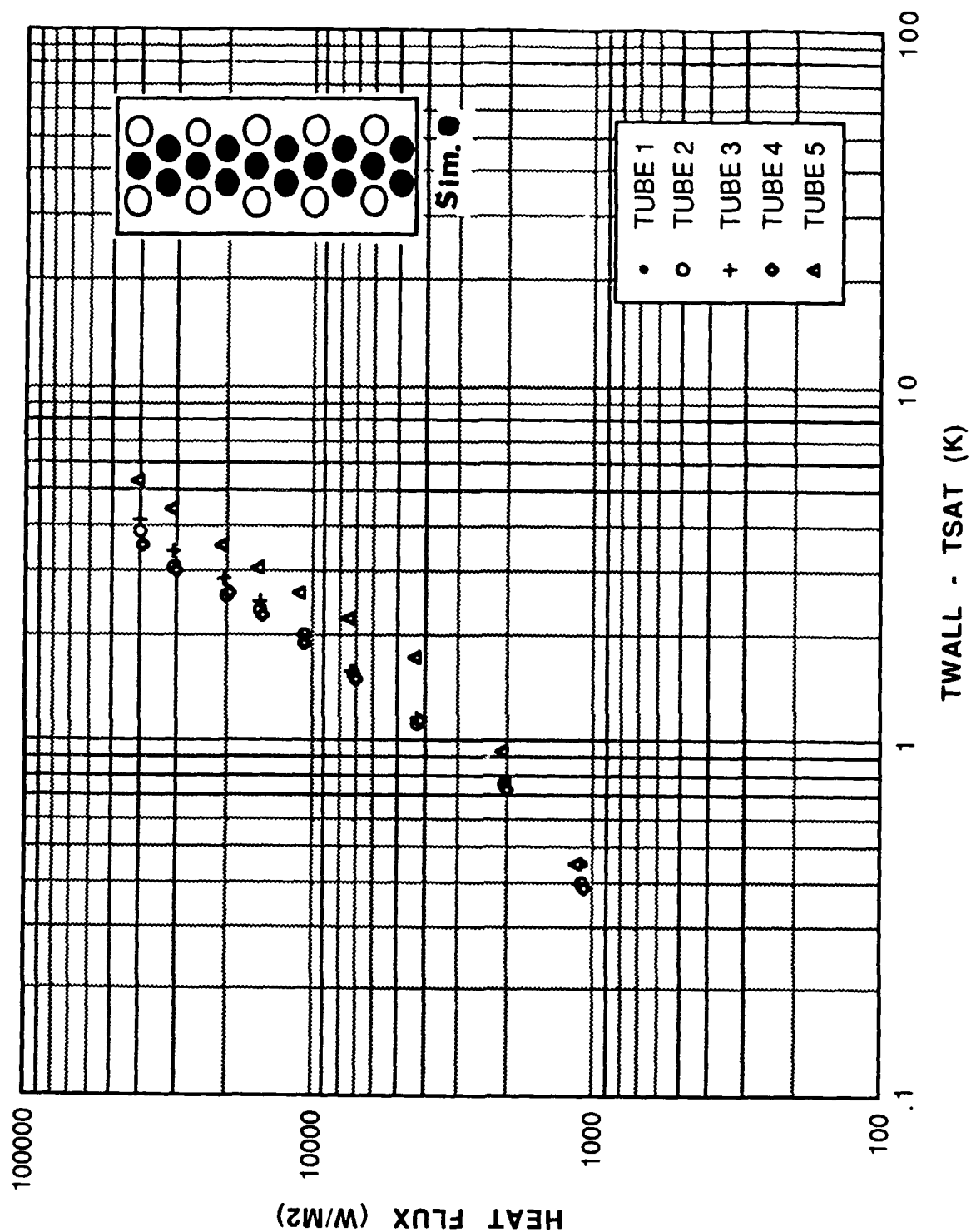
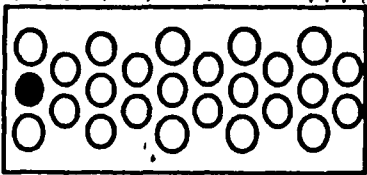


Figure 51. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 6% Oil



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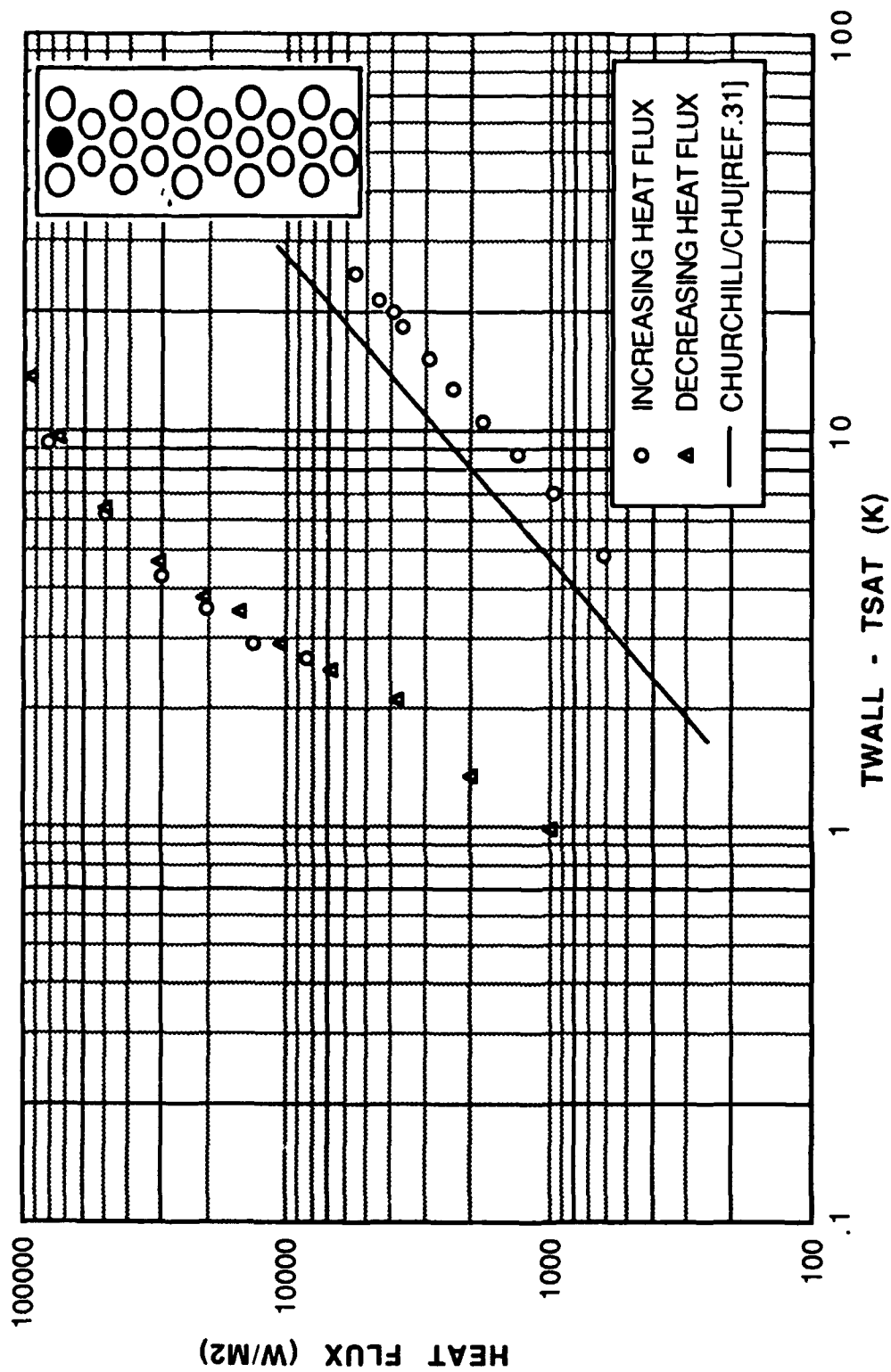


Figure 53. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 10% Oil

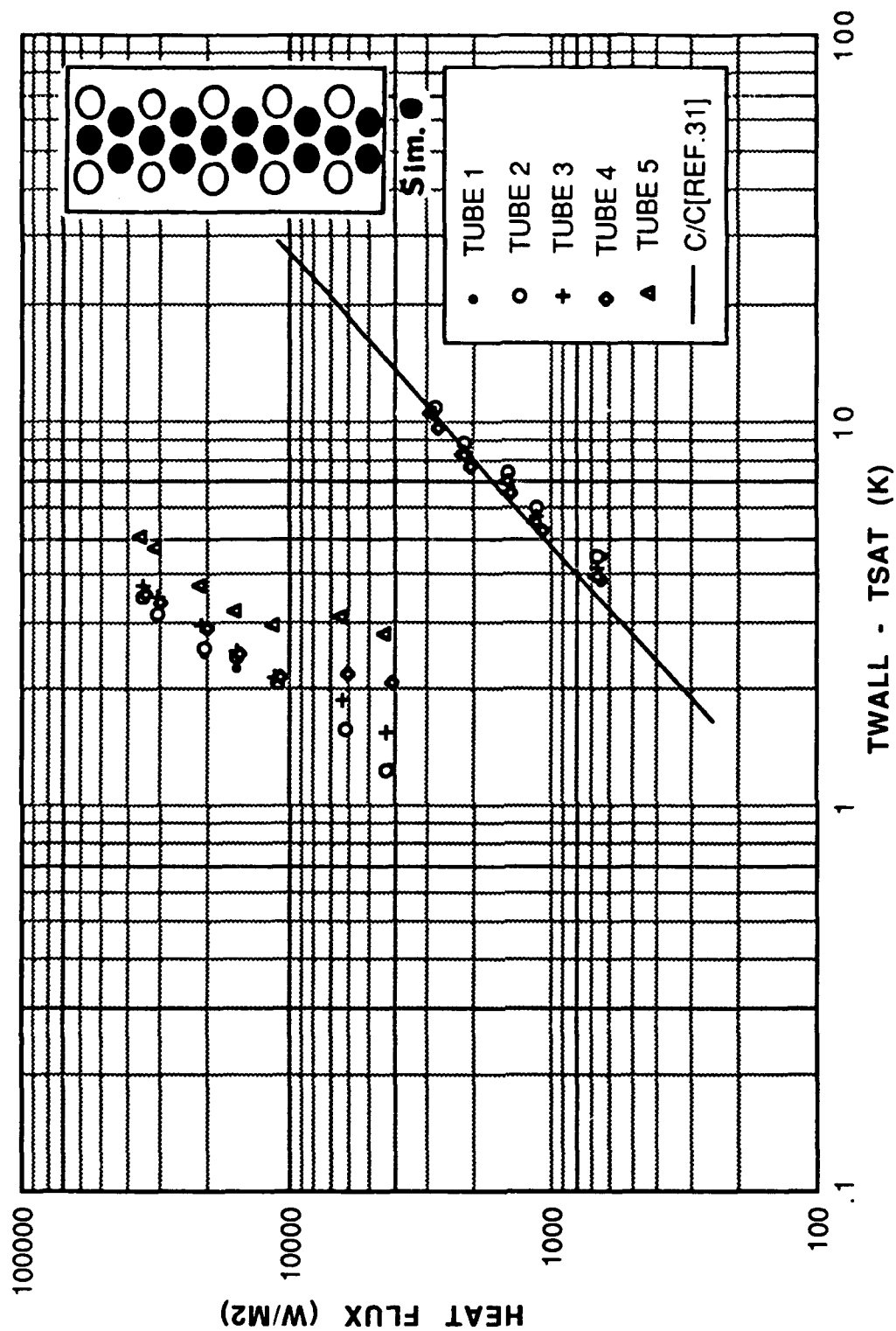


Figure 54. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 10% Oil

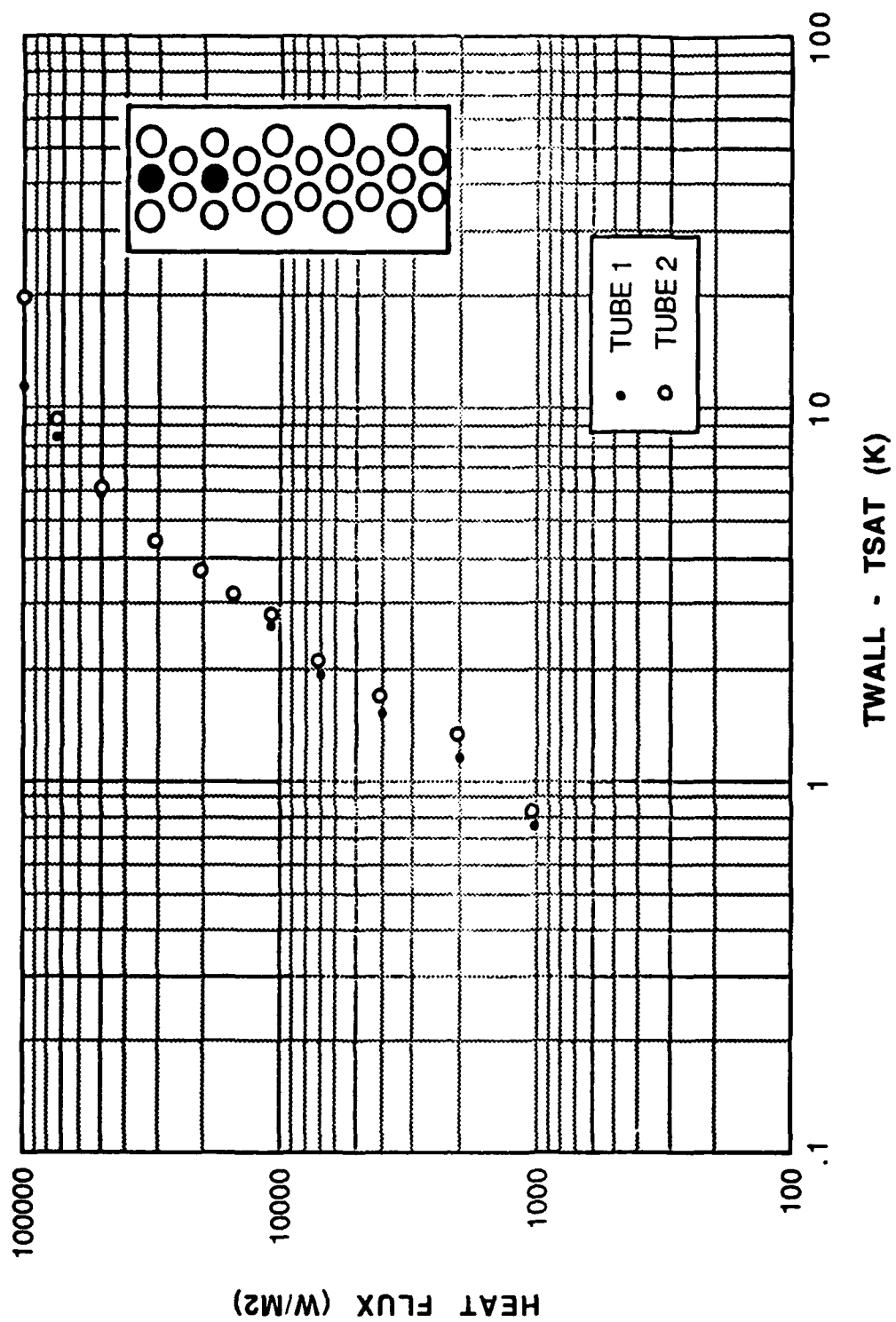


Figure 55. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 10% Oil

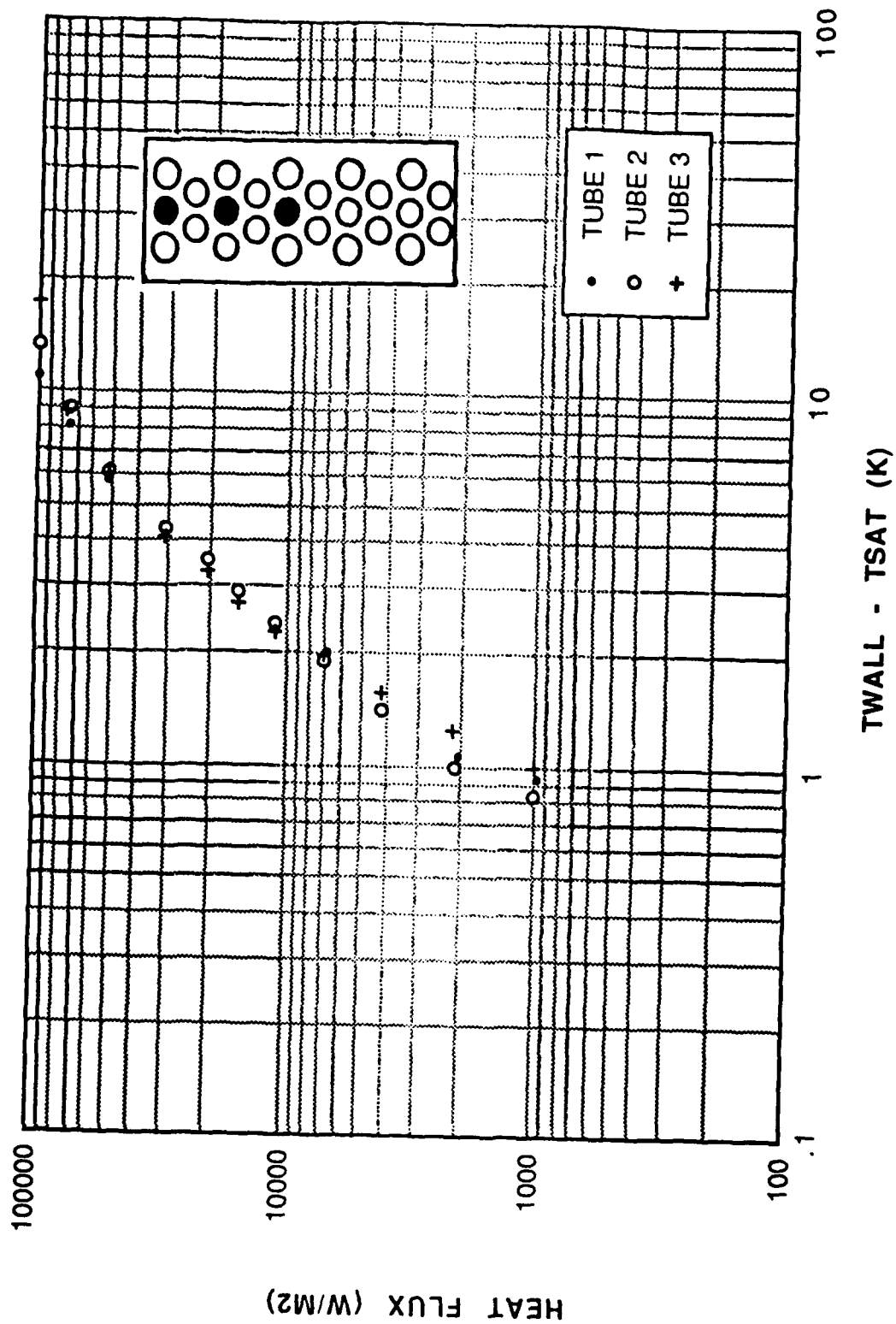


Figure 56. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 10% Oil

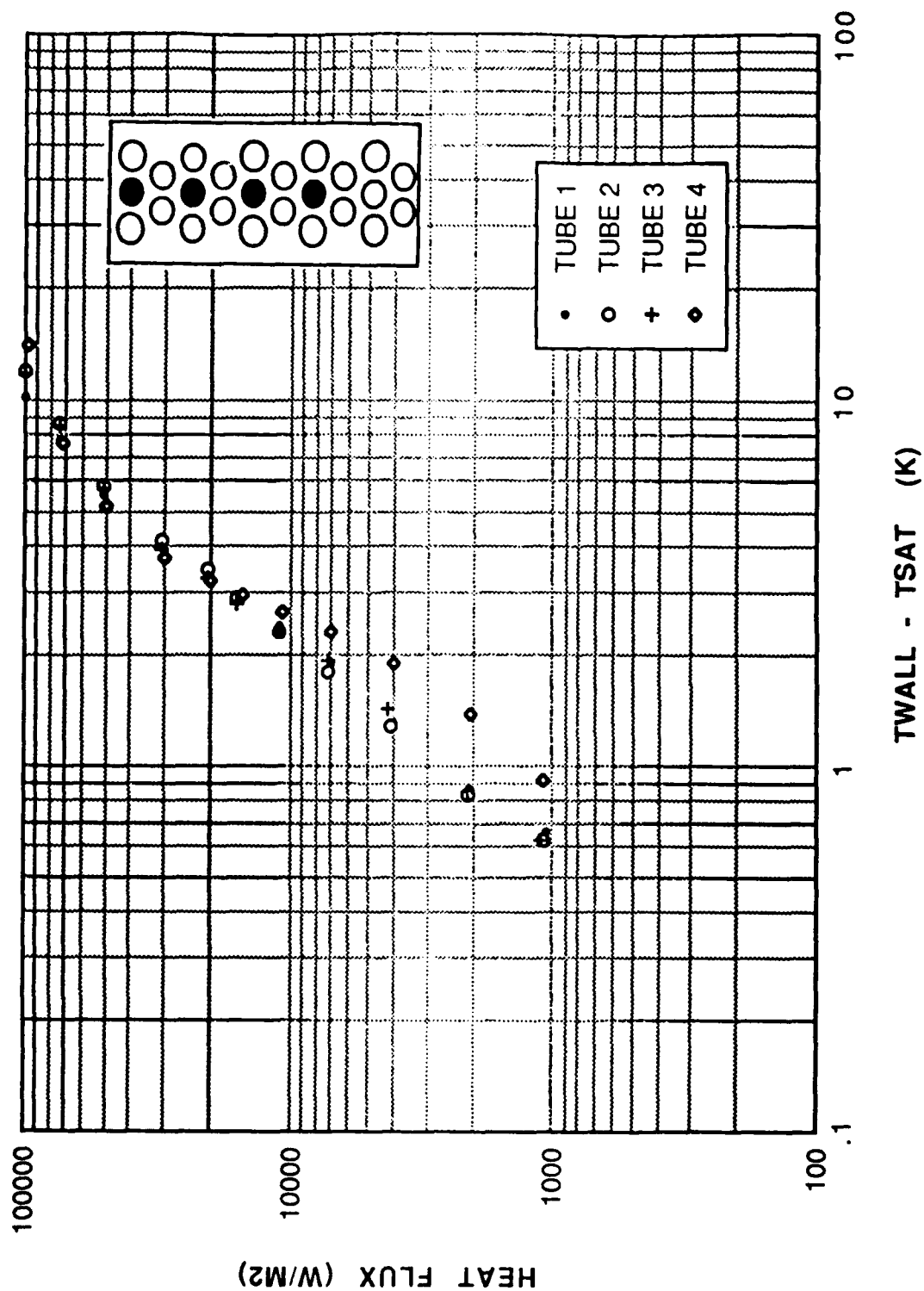


Figure 57. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 10% Oil



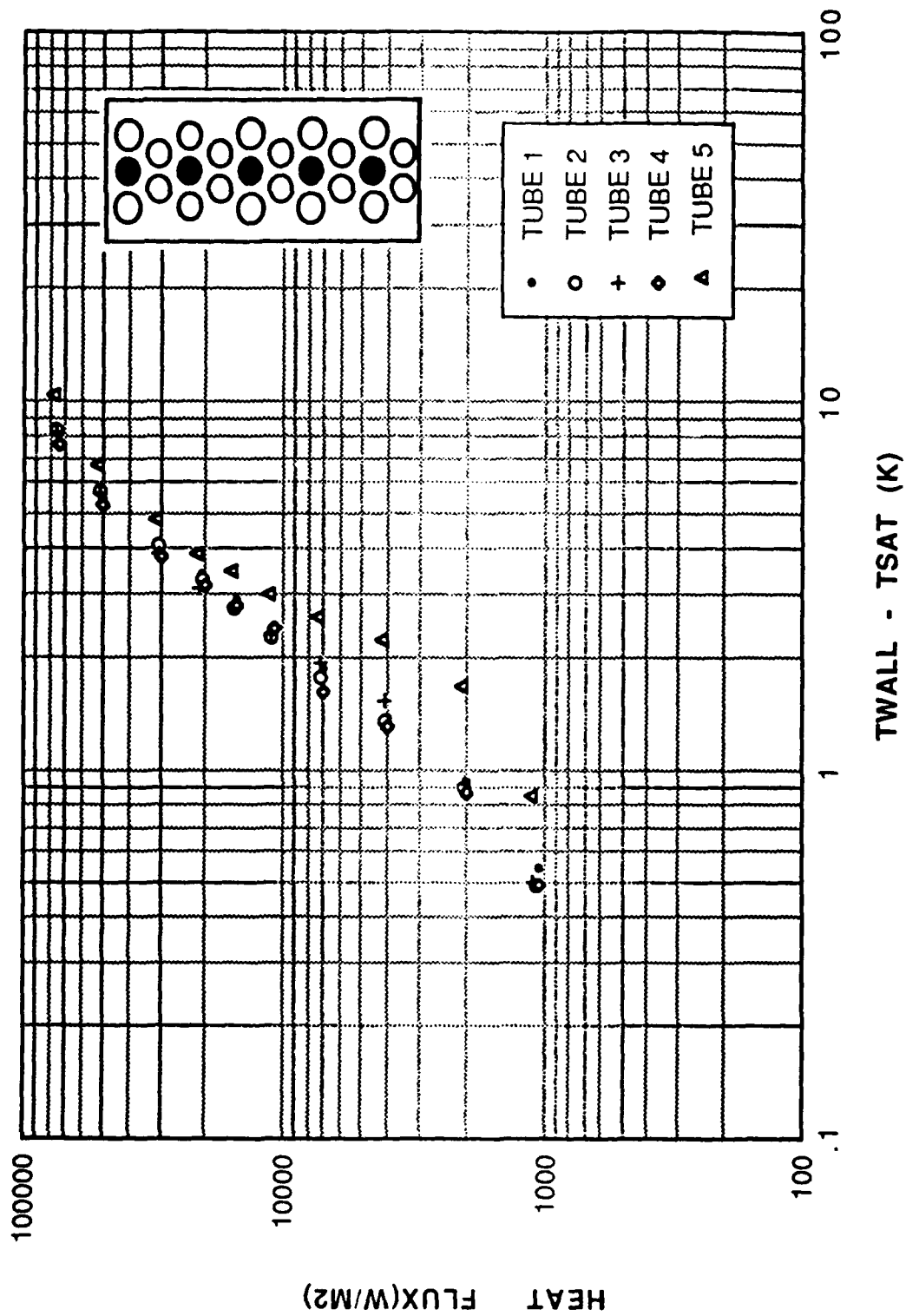


Figure 58. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 10% Oil

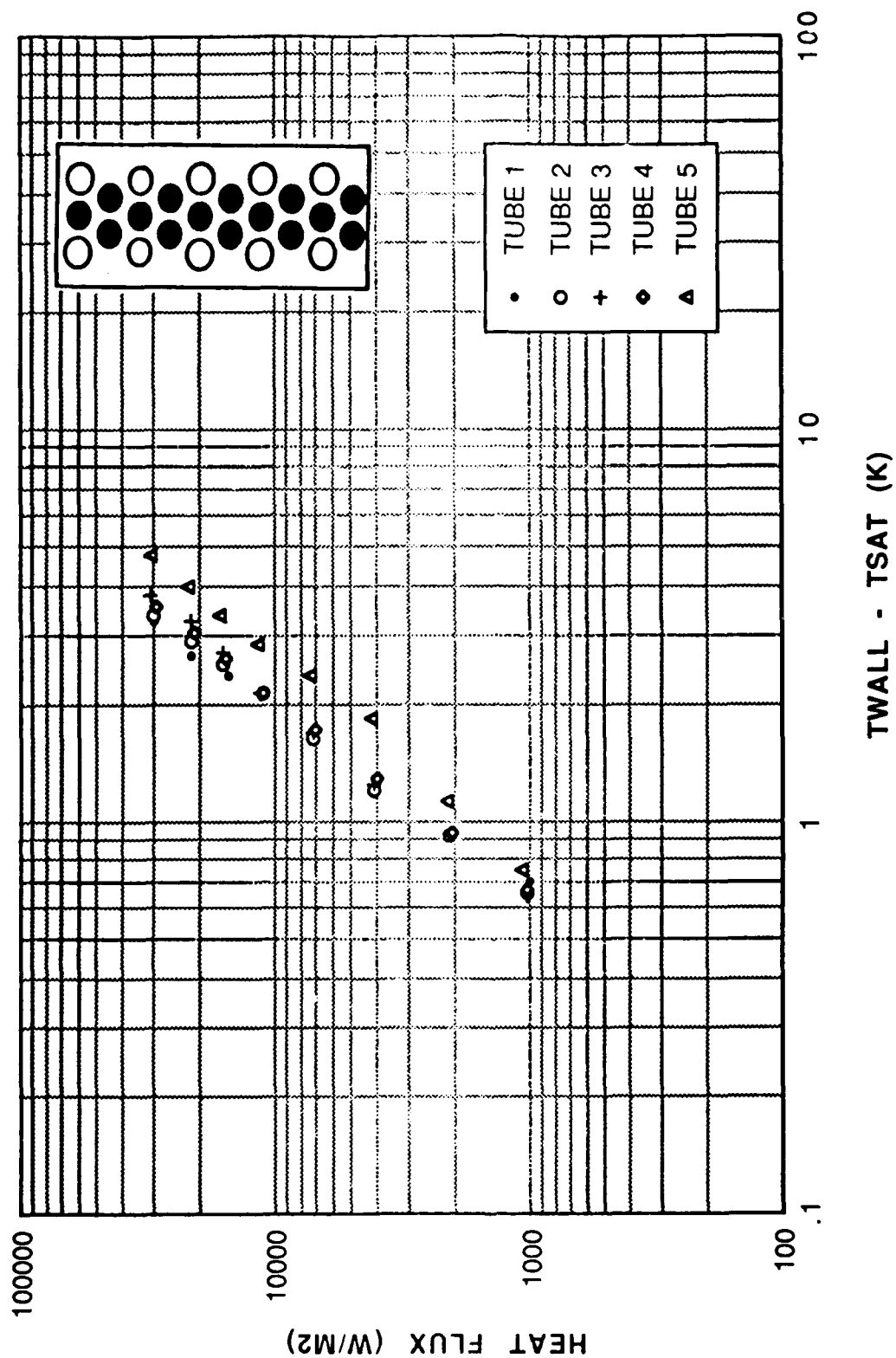


Figure 59. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 10% Oil

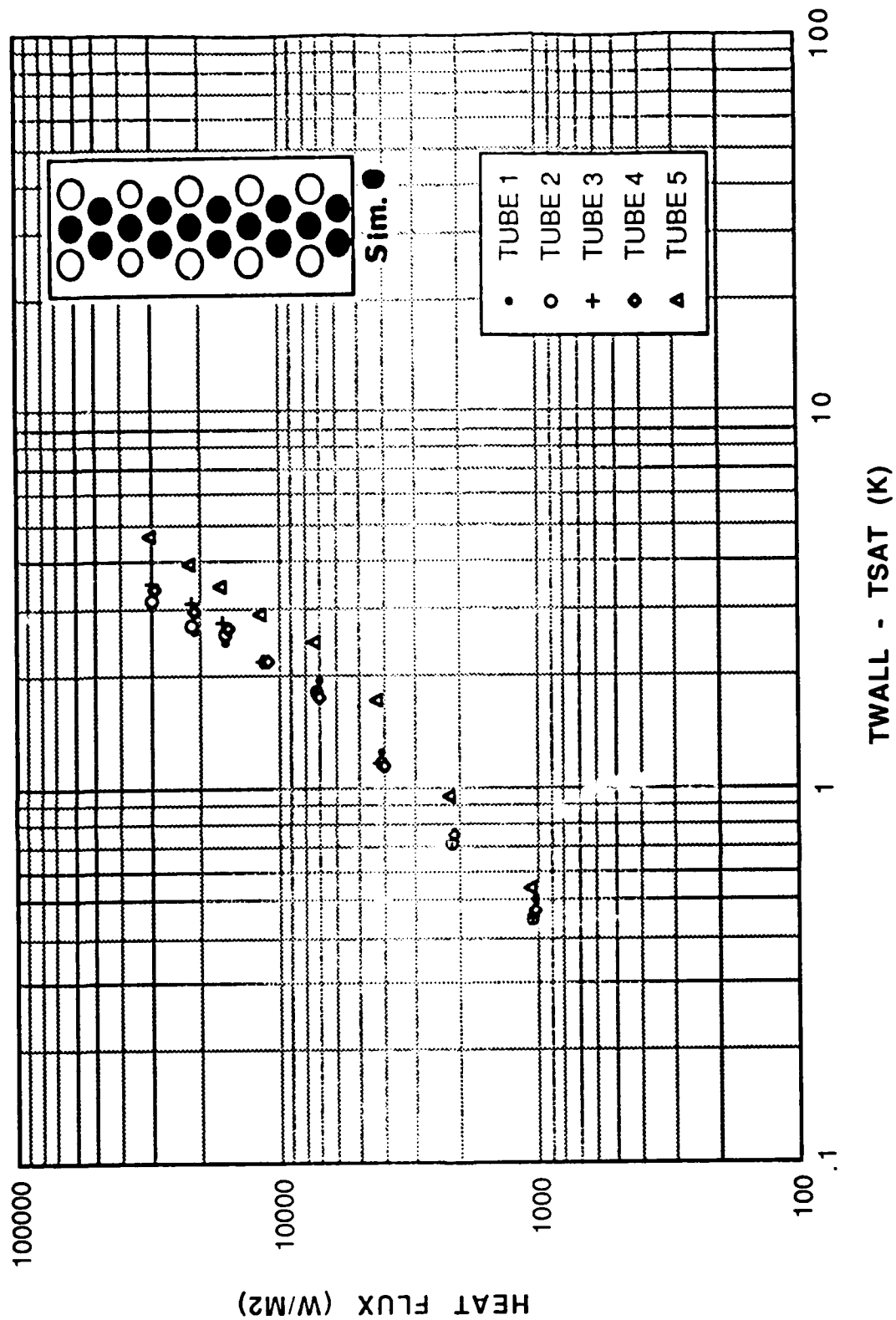


Figure 60. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 10% Oil

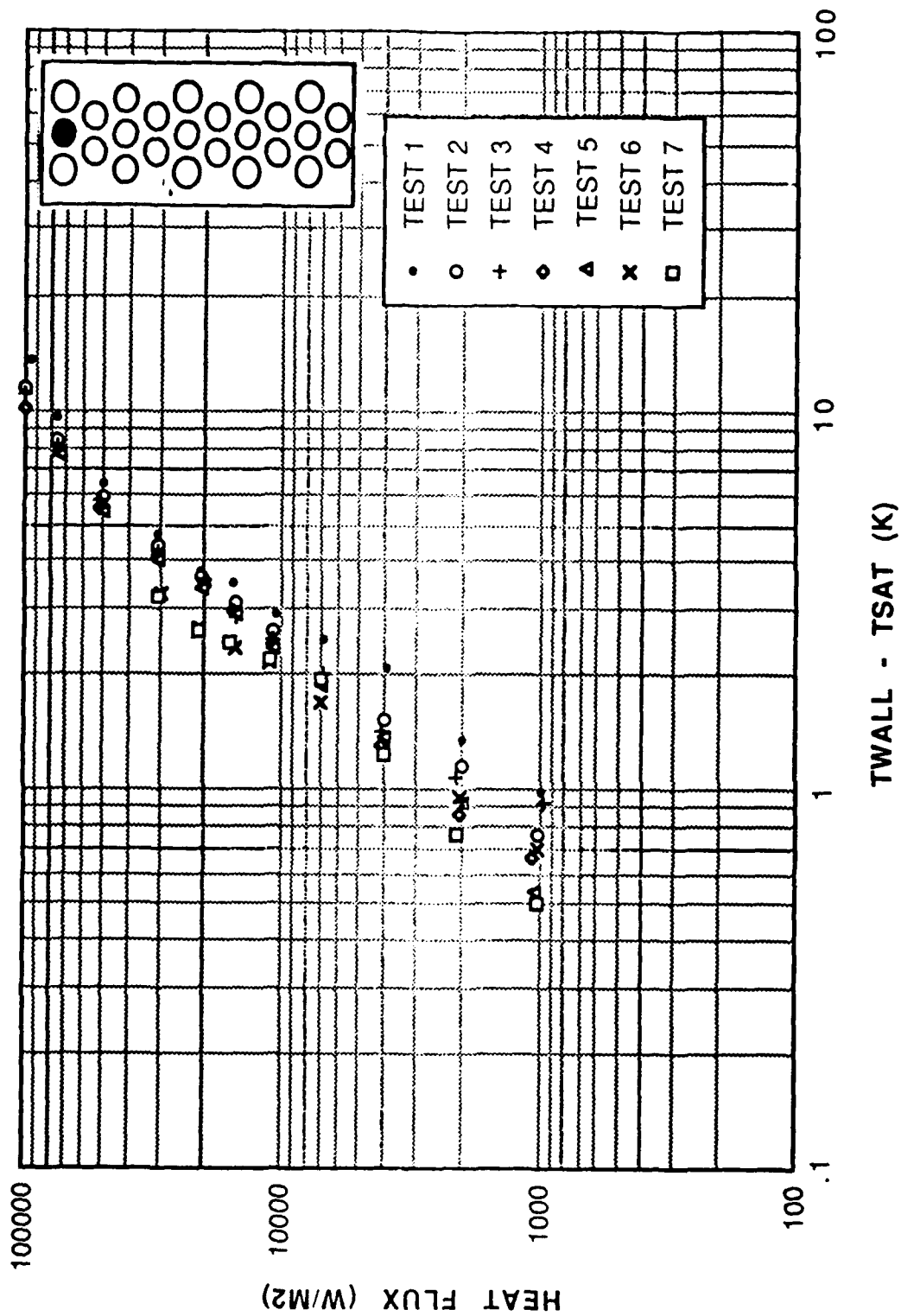


Figure 61. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in R-114 with 10% Oil

# Data from "TEST1 INC- 0,1,2,3,6,10%"

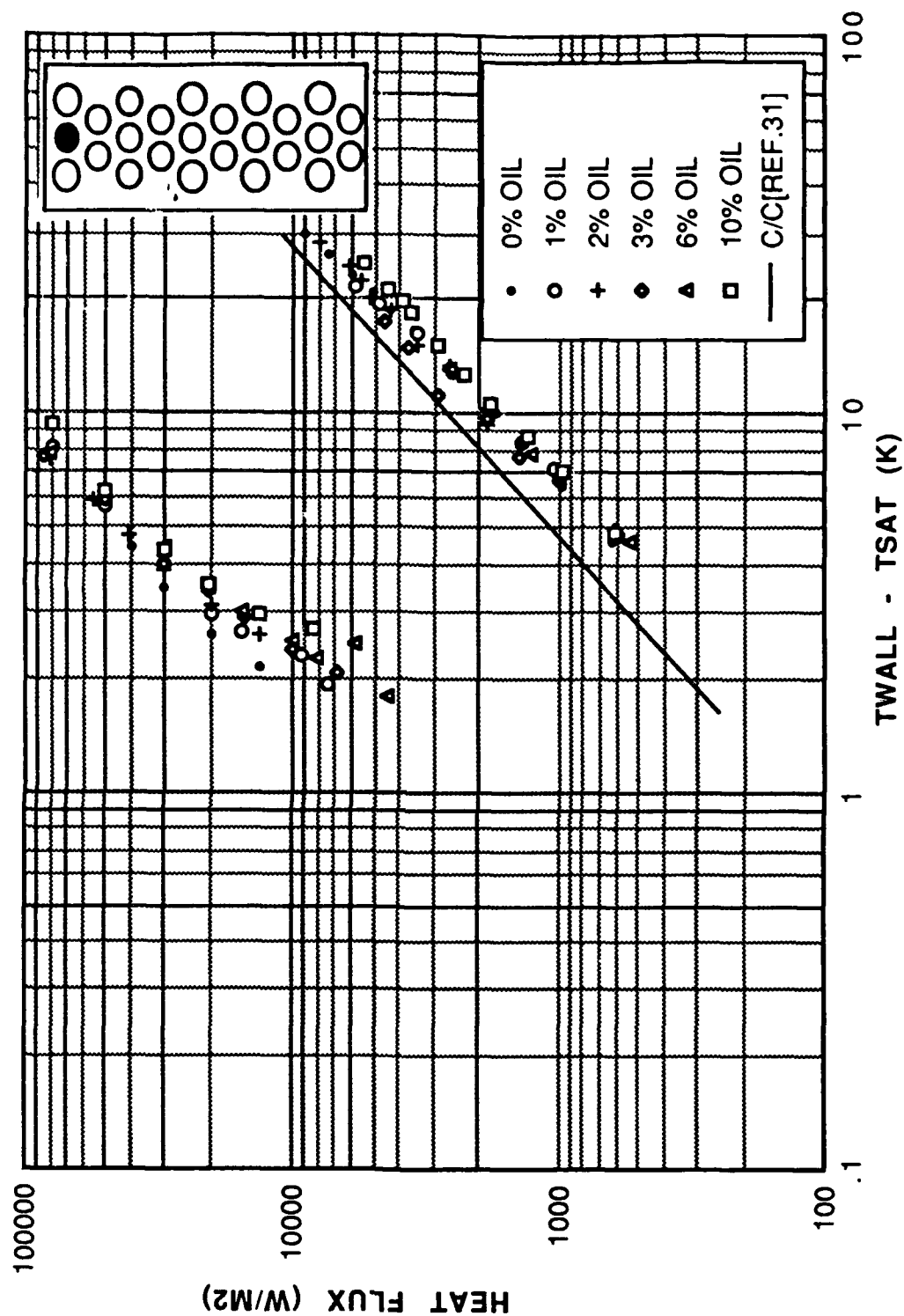


Figure 62. Comparison of Test One for Increasing Heat Flux in R-114 /Oil Mixtures

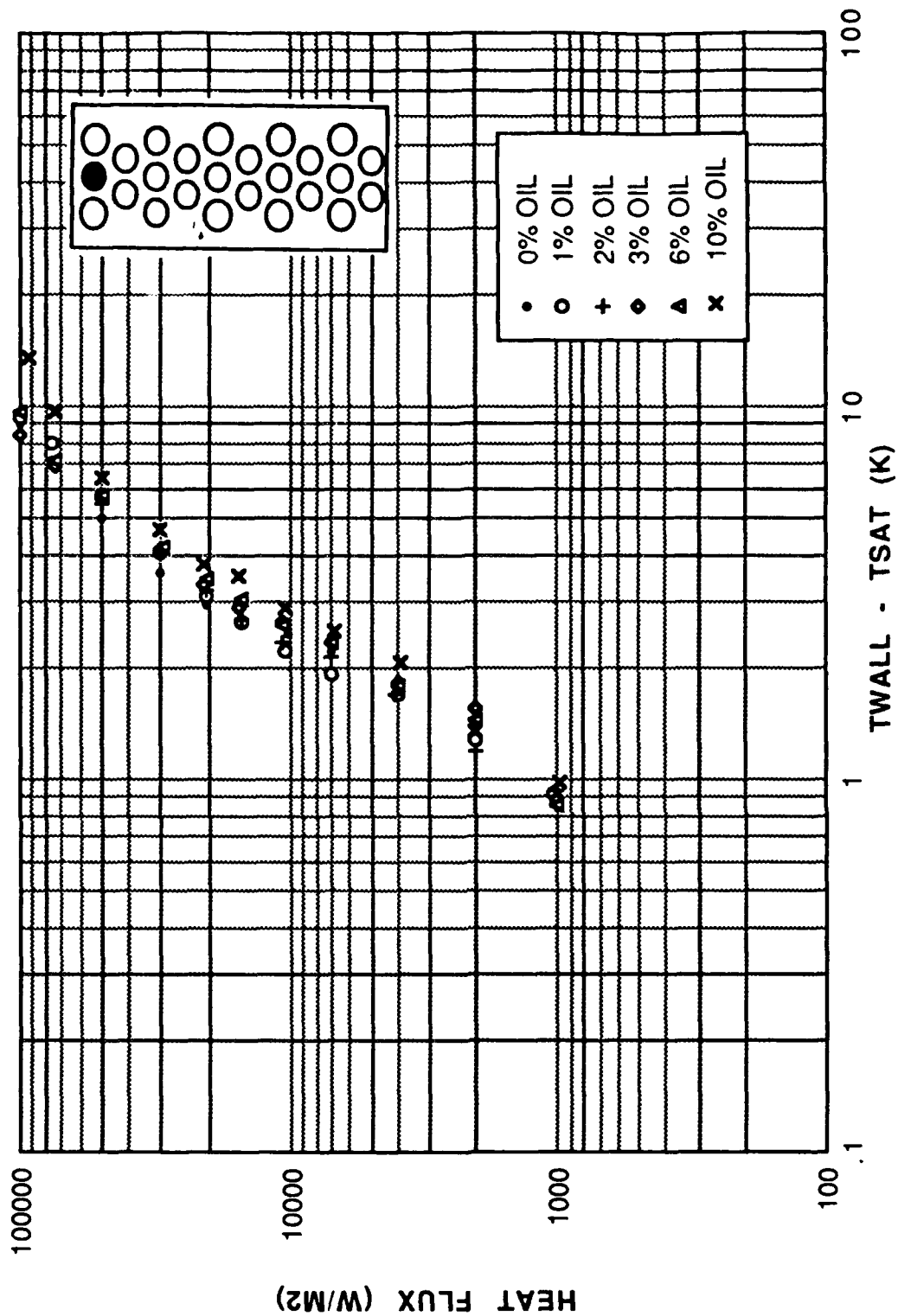


Figure 63. Comparison of Test One for Decreasing Heat Flux in R-114 /Oil Mixtures

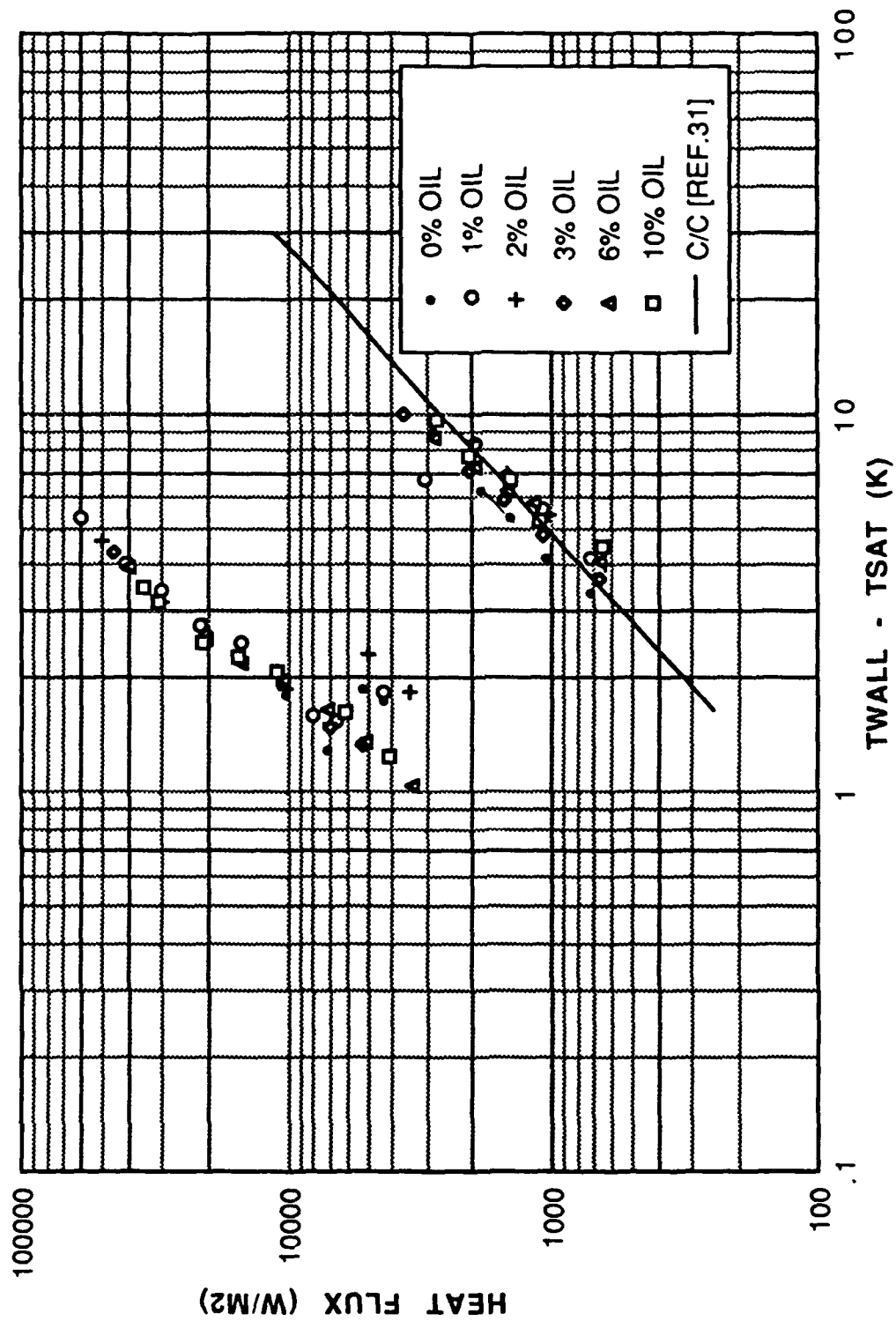


Figure 64. Comparison of Tests One to Seven Tube One for Increasing Heat Flux in R-114/Oil Mixtures

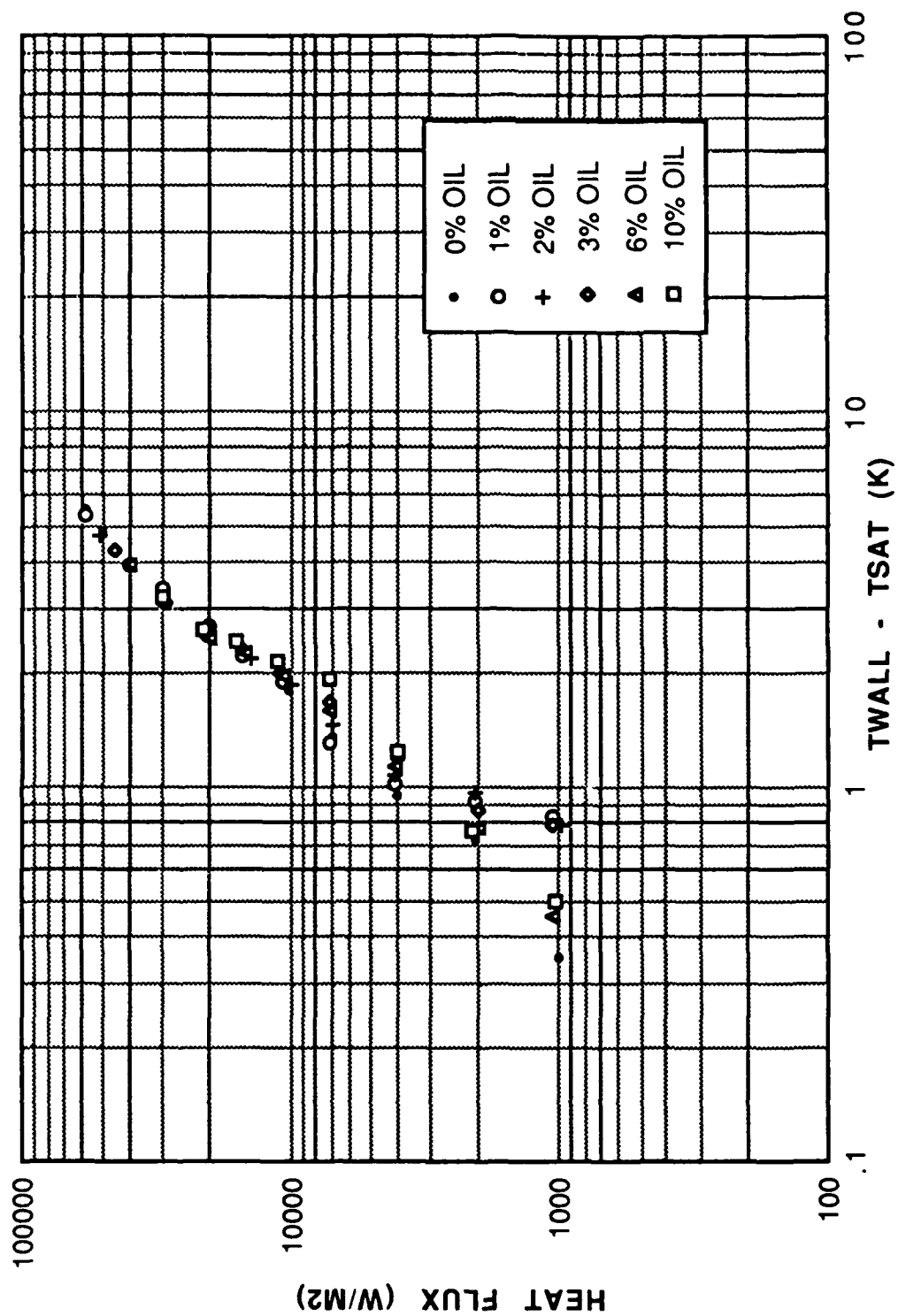


Figure 65. Comparison of Tests One to Seven Tube One for Decreasing Heat Flux in R-114/Oil Mixtures



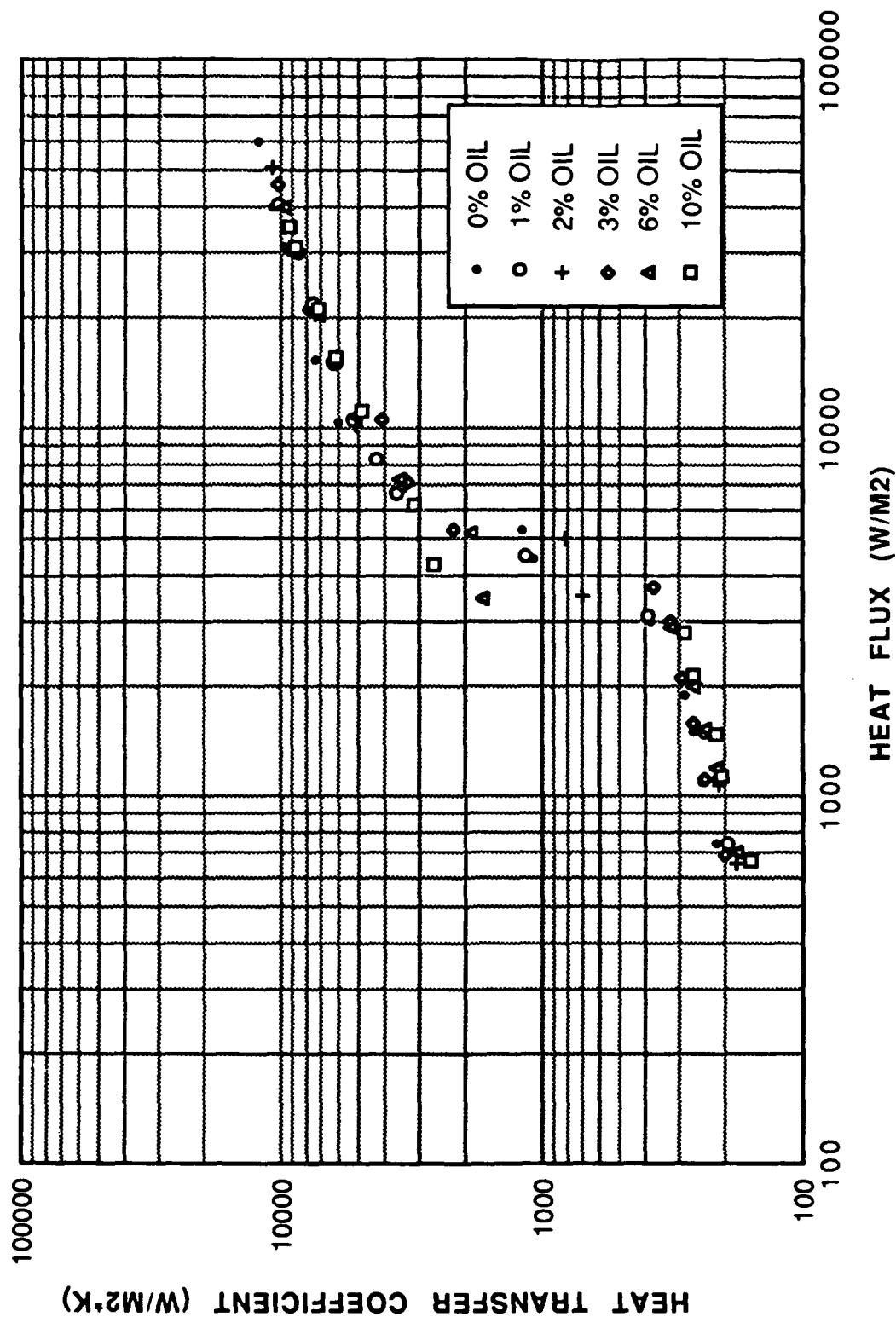


Figure 66. Mean Bundle Heat-Transfer Coefficient for Increasing Heat Flux in R-114/Oil Mixtures

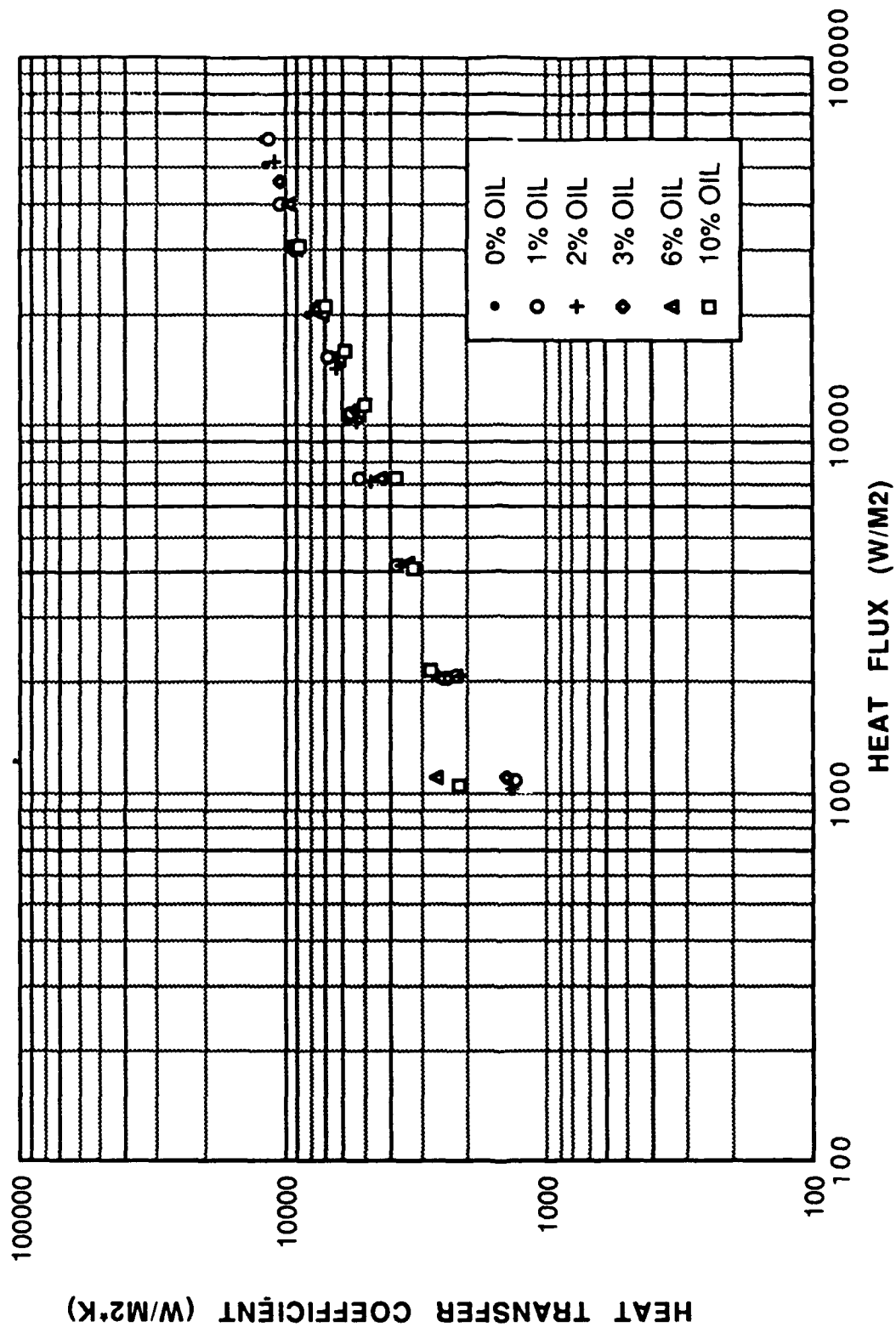


Figure 67. Mean Bundle Heat-Transfer Coefficient for Decreasing Heat Flux in R-114/Oil Mixtures

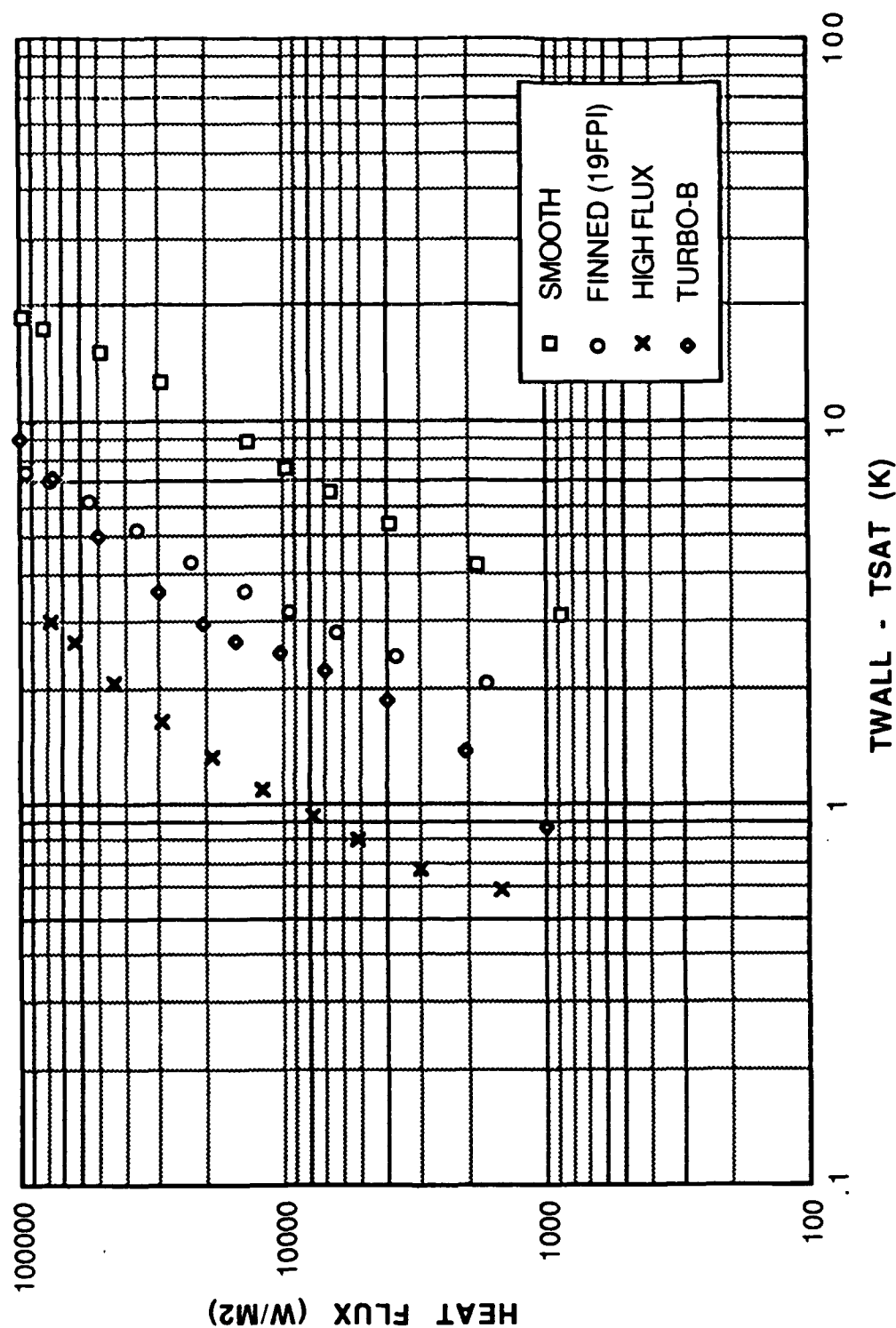


Figure 68. Test One Comparison of Turbo-B, Smooth, Finned, and High Flux Tube Bundles for Decreasing Heat Flux in Pure R-114

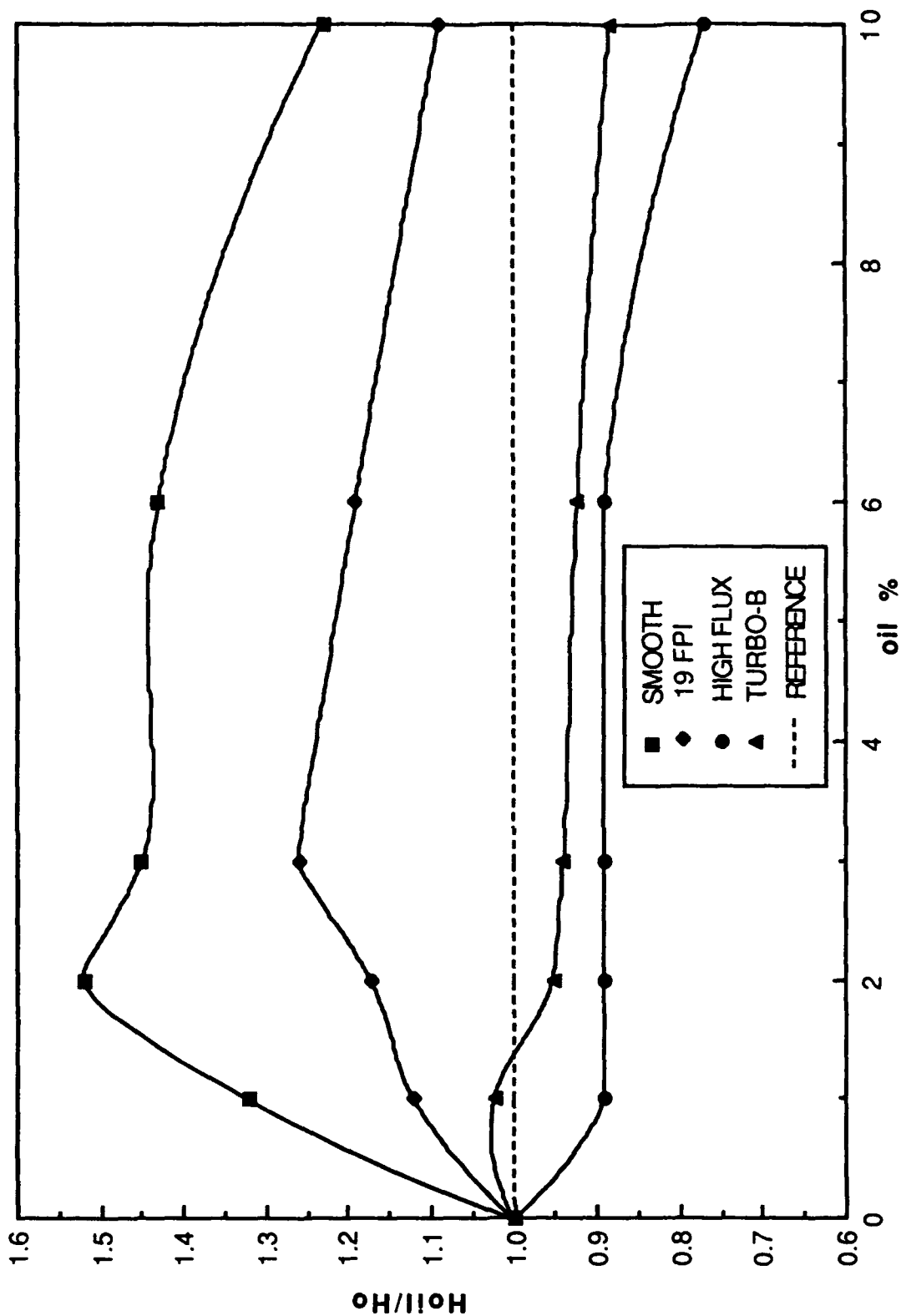


Figure 69. Ratio of Mean Bundle Heat-Transfer Coefficient With Oil to Heat-Transfer Coefficient Without Oil for Different Oil Percentages at a Heat Flux of  $15 \text{ kW/m}^2$

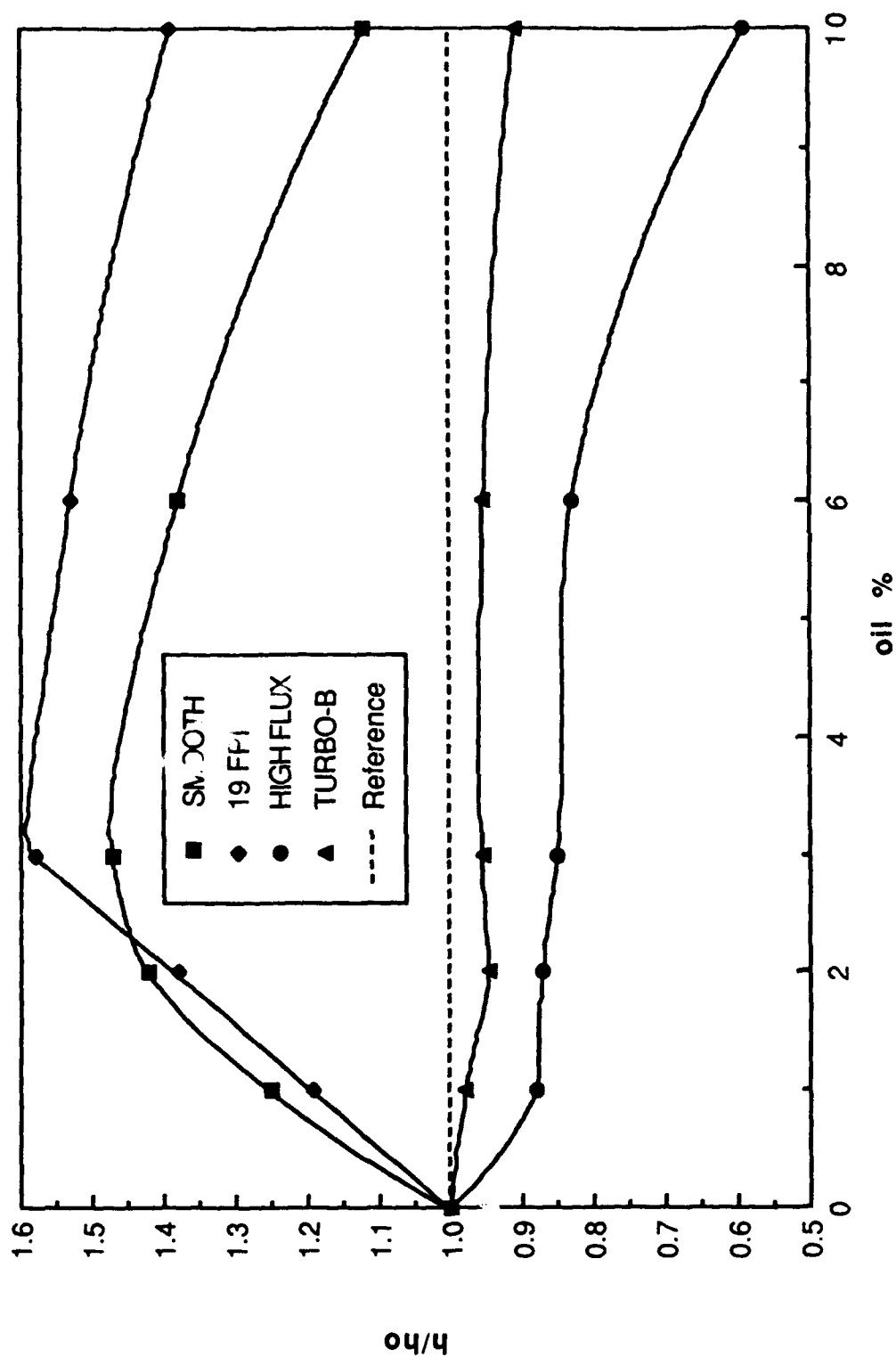


Figure 70. Ratio of Mean Bundle Heat-Transfer Coefficient With Oil to Heat-Transfer Coefficient Without Oil for Different Oil Percentages at a Heat Flux of 30 kW/m<sup>2</sup>

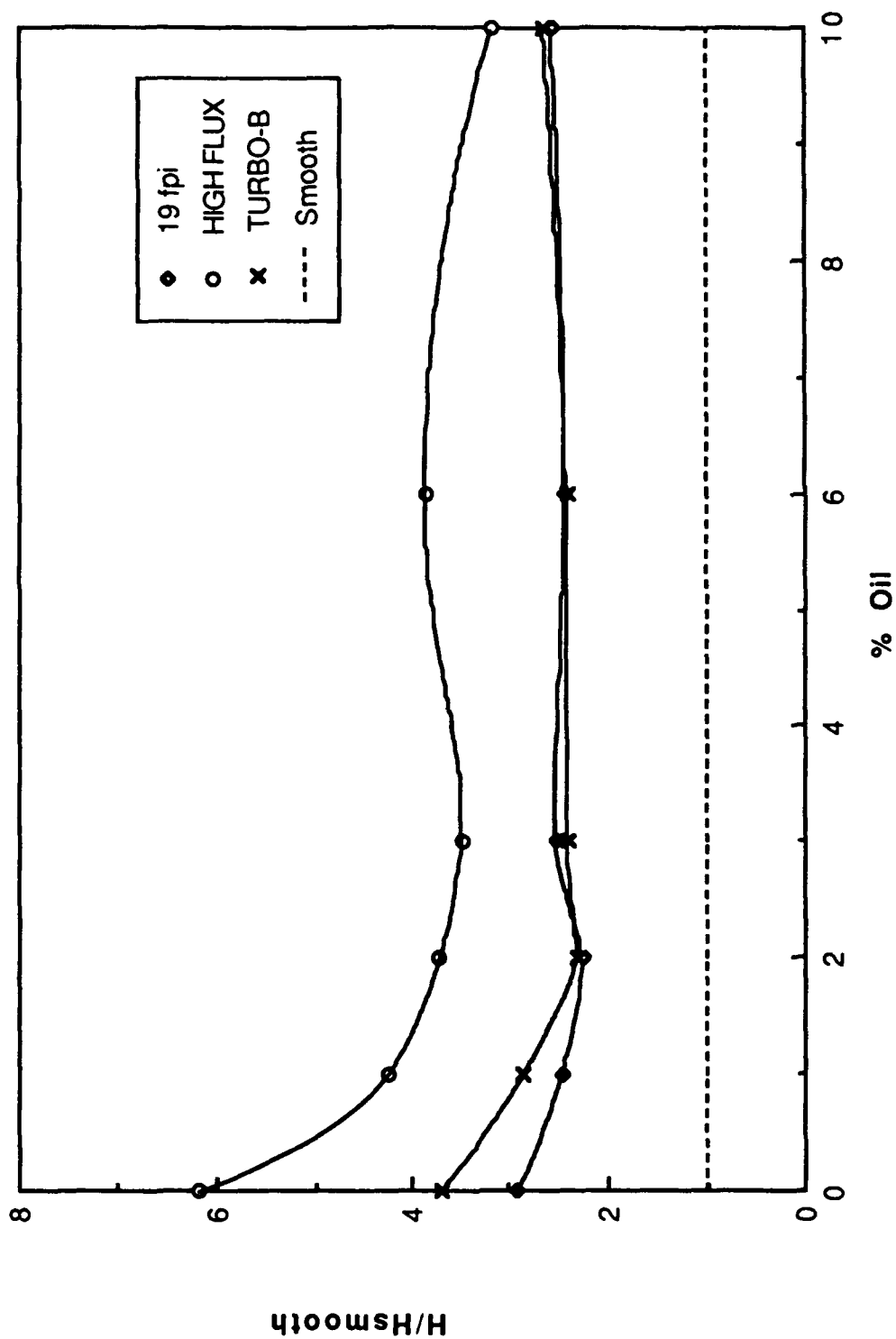


Figure 71. Ratio of Mean Bundle Heat-Transfer Coefficient of Enhanced Tube to Heat-Transfer Coefficient of Smooth Tube for Different Oil Percentages at a Heat Flux of  $15 \text{ kW/m}^2$

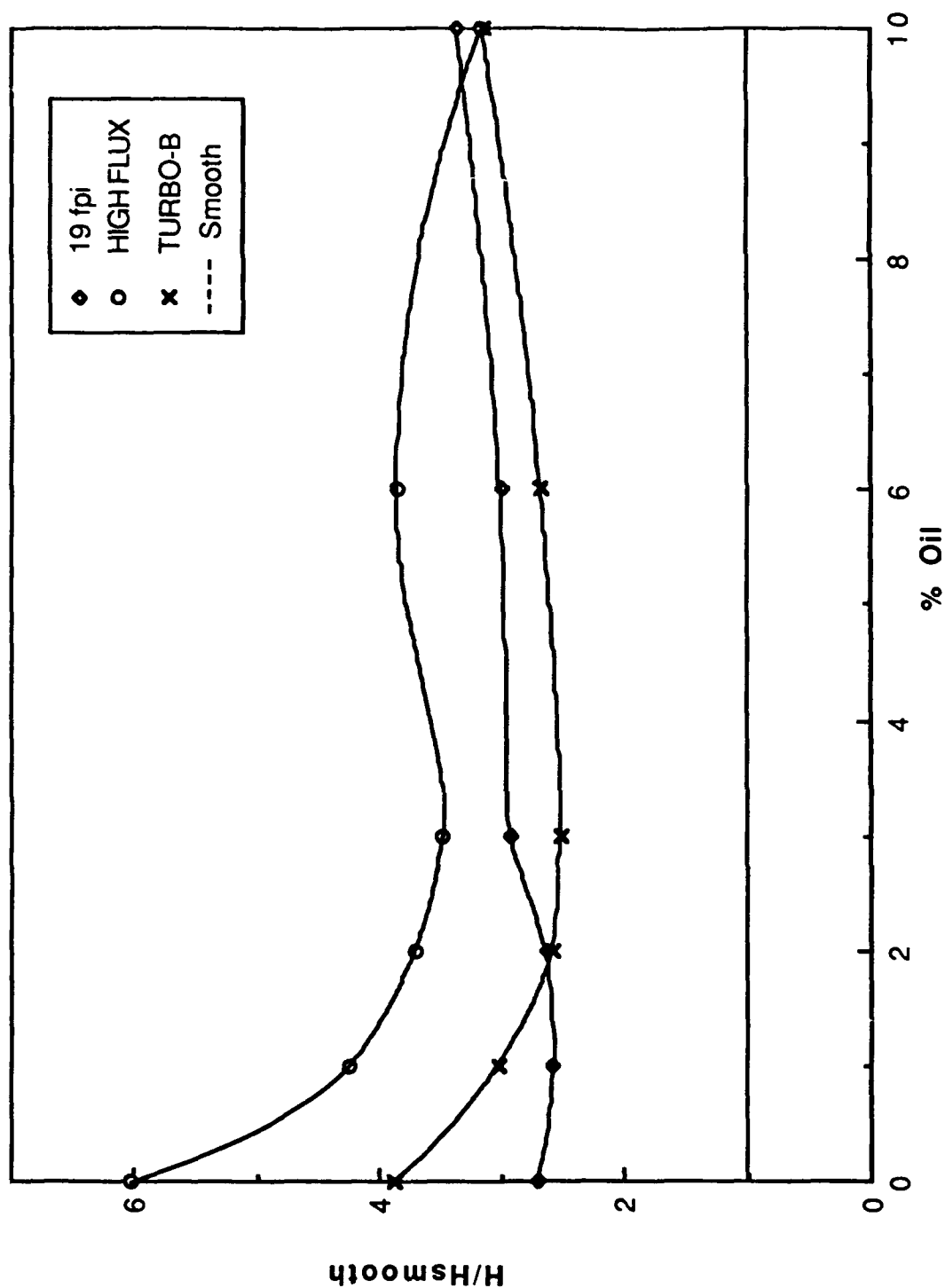


Figure 72. Ratio of Mean Bundle Heat-Transfer Coefficient of Enhanced Tube to Heat-Transfer Coefficient of Smooth Tube for Different Oil Percentages at a Heat Flux of 30 kW/m<sup>2</sup>

## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

Nucleate boiling data of R-114 at atmospheric pressure were obtained using a small bundle of Turbo-B copper tubes. The data were obtained for both increasing and decreasing heat flux and at different oil concentrations. Based upon the results pertaining to this particular bundle and apparatus, the following conclusions may be made:

#### 1. Natural Convection Region

a. For a single upper tube, a second lower tube directly below when turned on does increase the heat transfer performance of the upper tube, however when additional lower tubes are heated no net increase in performance occurs.

b. The presence of heated lower tubes in the bundle reduces the incipient boiling point of the upper tubes and the tubes tend to nucleate 'in order' (ie. top tube first, bottom tube last).

c. The effect of adding oil to the refrigerant (up to 10%) reduces the heat-transfer coefficient slightly (approximately 10-15%) due to changes in the fluid properties.

#### 2. Boiling Region

a. For pure R-114, the presence of heated lower tubes on the top tube causes no enhancement at high heat fluxes ( $> 20 \text{ kW/m}^2$ ), but at low heat fluxes ( $< 20 \text{ kW/m}^2$ ), there is a significant enhancement due to convective effects.



b. At very low heat fluxes ( $<2 \text{ kW/m}^2$ ), the presence of oil has little effect on the heat transfer performance of the top tube in the bundle. At higher heat fluxes ( $> 2 \text{ kW/m}^2$ ), the performance is enhanced by 10-15% at low concentrations, but is degraded up to 20% at 10% oil concentration at the highest heat fluxes.

c. At typical operating heat fluxes ( $15\text{--}30 \text{ kW/m}^2$ ), the bundle performance is reduced between 5-15% with oil.

#### B. RECOMMENDATIONS FOR FUTURE WORK

1. Conduct experiments with varying pool height, but keep the local pressure at each tube constant by simultaneously varying the vapor pressure above the pool.

2. Additional experiments with R-113 and R-114 should be conducted to investigate explosive (R-114) and partial (R-113) incipience at the onset of nucleation varying the time at the incipience.

3. Some instrumentation should be added such that the flowrates through the bundle can be determined. From these measurements, vapor quality can be determined.

4. Metal guide plates should be manufactured and placed on each side between the simulation tube bundle and the tube bundle itself. This further channels the flow of refrigerant thru the bundle at high heat fluxes.

5. Attention needs to be given to the question of refrigerant disposal. There are reclamation projects undertaken by most manufacturers; however, a method still needs to be found to remove the

refrigerant from the apparatus into a container suitable for such reclamation.

6. A high speed camera should be used to study the nucleation process and circulation patterns in more detail in the bundle. Neutrally buoyant particles might be placed in the pool to facilitate study of circulation patterns within the bundle.

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# APPENDIX A: LIST OF DATA FILE

**Table 3. DATA FILE NAMES FOR TURBO-B  
TUBE BUNDLE EXPERIMENTS**

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TB10001H	38	1 (15)	0	0	0
TBD0001H	38	1 (15)	0	0	0
TB10001I	25	1 (13)	0	0	0
TBD0001I	22	1 (13)	0	0	0
TB10001J	34	1	0	0	0
TBD0001J	25	1	0	0	0
TB10002A	38	2	0	0	0
TBD0002	25	2	0	0	0
TB10003A	33	3	0	0	0
TBD0003	27	3	0	0	0
TB10004	36	4	0	0	0
TBD0004	24	4	0	0	0
TB10005	34	5	0	0	0
TBD0005	24	5	0	0	0
TB10006	32	5	0	5	0
TBD0006	26	5	0	5	0

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBI0007	31	5	0	5	5
TBD0007	24	5	0	5	5
TBI0101	33	1	1	0	0
TBD0101	23	1	1	0	0
TBI0107	29	5	1	5	5
TBD0107	26	5	1	5	5
TBI0201	38	1	2	0	0
TBD0201	22	1	2	0	0
TBI0207	25	5	2	5	5
TBD0207	20	5	2	5	5
TBI0301	34	1	3	0	0
TBD0301	25	1	3	0	0
TBD0302	24	2	3	0	0
TBD0303	22	3	3	0	0
TBD0304	24	4	3	0	0
TBD0305	24	5	3	0	0
TBD0306	21	5	3	5	0
TBI0307	26	5	3	5	5
TBD0307	21	5	3	5	5
TBI0601	32	1	6	0	0

FILE NAME	NUMBER OF DATA POINT	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBD0601	22	1	6	0	0
TBD0602	22	2	6	0	0
TBD0603	24	3	6	0	0
TBD0604	22	4	6	0	0
TBD0605	24	5	6	0	0
TBD0606	21	5	6	5	0
TBI0607	27	5	6	5	5
TBD0607	21	5	6	5	5
TBI1001	33	1	10	0	0
TBD1001	22	1	10	0	0
TBD1002	27	2	10	0	0
TBD1003	24	3	10	0	0
TBD1004	24	4	10	0	0
TBD1005	23	5	10	0	0
TBD1006	16	5	10	5	0
TBI1007	24	5	10	5	5
TBD1007	17	5	10	5	5
TBI0001A	24	1	0	0	0
TBI0001C	27	1(15)	0	0	0
TBI0001D	33	1(13)	0	0	0



FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBI0001E	33	1	0	0	0
TBI0001F	38	1	0	0	0
TBI0001G	38	1	0	0	0

## APPENDIX B: SAMPLE CALCULATIONS

Data set number 1 Tube 1 of experiment TBD1005 (Turbo-B tube, decreasing heat flux, 10% oil concentration, test 5) was used for the sample calculations in order to validate the program used for data acquisition DRP4RH. The working fluid was R-114.

### 1. Test tube dimensions

$$D_{tc} = 11.60 \text{ mm}$$

$$D_o = 14.15 \text{ mm}$$

$$D_i = 12.70 \text{ mm}$$

$$L = 203.2 \text{ mm}$$

$$L_u = 25.4 \text{ mm}$$

### 2. Measured Parameters

$$T1 = 10.62 \text{ }^{\circ}\text{C}$$

$$T2 = 10.94 \text{ }^{\circ}\text{C}$$

$$T3 = 9.96 \text{ }^{\circ}\text{C}$$

$$T4 = 10.90 \text{ }^{\circ}\text{C}$$

$$T5 = 10.04 \text{ }^{\circ}\text{C}$$

$$T6 = 9.07 \text{ }^{\circ}\text{C}$$

$$T1d1 = 2.27 \text{ }^{\circ}\text{C}$$

$$T1d2 = 2.21 \text{ }^{\circ}\text{C}$$

$$Aas = 3.513 \text{ V}$$

$$V_{as} = 3.189 \text{ V}$$

### 3. Calculations

The heaters power is first calculated for

$$q = V_{as}(V) \times A_{as}(V) \times 60(V/V) \times 1(A/V)$$

Note: The multiplication factors of volts and amp sensors are 60 and 1, respectfully.

Therefore:

$$q = (3.189)(3.513)(60V/V)(1A/V)$$

$$q = 672.19 \text{ Watts}$$

The tube inside wall temperature is obtained from the average of all six thermocouple readings.

$$\bar{T}_{wi} = \frac{1}{6} \sum_{n=1}^6 T_n$$

$$= 1/6(10.62 + 10.94 + 9.96 + 10.90 + 10.04 + 9.07)$$

$$= 10.25 \text{ }^{\circ}\text{C}$$

The tube outside temperature is calculated by knowing the inside wall temperature using Fourier's Conduction Law. Uniform radial conduction is assumed.

$$\bar{T}_{wo} = \bar{T}_{wi} - \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

where the second term on the right hand side is the Fourier conduction term. If we define this term as

$$\phi = \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

and

$$\theta_b = \bar{T}_{wo} - T_{sat_c}$$

where  $k_{cu}$  is the thermal conductivity of copper and is calculated as follows

$$k_{cu} = 434.0 - [0.112(\bar{T}_{wi})]$$

$$k_{cu} = 434.0 - [0.112(283.25)]$$

$$k_{cu} = 402.28 \text{ W/mK}$$

now

$$\bar{T}_{wo} = \bar{T}_{wi} - \frac{672.19[\ln(\frac{14.15}{11.60})]}{2\pi(402.28)(.2032)}$$

$$\bar{T}_{wo} = (10.25 - .2601)^\circ \text{C}$$

$$\bar{T}_{wo} = 9.98^\circ \text{C}$$

The liquid saturation temperature at the top of the tube bundle is

$$T_{sat} = \frac{t_{ld1} + T_{ld2}}{2}$$

$$T_{sat} = \frac{2.27 + 2.21}{2}$$

$$T_{sat} = 2.24^{\circ}C$$

In order to calculate the local saturation temperature for each tube, correction factors are needed to account for hydrostatic pressure differences between the tube locations and the liquid free surface. This difference is calculated by:

$$\Delta P = \rho (g) (ht)$$

For the top tube in the bundle which is 0.124 m below the thermocouple measuring pool temperature.

$$\Delta P = 1523.12 (9.81) (0.124)$$

$$\Delta P = 1852.78 \text{ Pa}$$

For 1852.78 Pa pressure difference, corrected saturation temperature is obtained by adding 0.04 °C (from standard tables for R-114) to  $T_{sat}$ . Corrected  $T_{sat}$  is:

$$T_{sat_c} = (2.24 + 0.04)^{\circ}C$$

$$T_{sat_c} = 2.28^{\circ}C$$

Therefore, the wall superheat can be obtained by the following:

$$\theta_b = \bar{T}_{wo} - T_{sat_c}$$

$$\theta_b = (9.98 - 2.28) ^\circ C$$

$$\theta_b = 7.70 ^\circ C$$

Now that the wall superheat is known, we need to calculate the heat flux and the heat-transfer coefficient. To do this, we know that the tube is 12 inches long and is heated in a eight inch center portion of the tube. The unheated lengths of the tube are a one inch and a three inch section on opposite ends of the tube. These unheated lengths have a fin effect during the heat transfer process to the evaporating refrigerant. In order to account for this, the following procedure was adopted for both one and three inch sections. Calculations are shown below for the one inch section. Heat transfer from the unheated end is calculated as heat from the base of the fin:

$$q_f = [(h_b)(p)(k_{cu})(A_c)]^{0.5}(\theta_b)(\tanh[(n)(L_c)])$$

where

$$p = \pi (D_o)$$

$$= \pi (.01415) \text{ m}$$

$$= .04445 \text{ m}$$

now

$$A_c = \pi/4(D_o^2 - D_i^2)$$

$$= \pi/4(.01415^2 - .01270^2)$$

$$= 3.0578 \times 10^{-5} \text{ m}^2$$

The corrected length of unenhanced surface at the end was calculated as follows

$$\begin{aligned} L_c &= L_u + (t/2) \\ &= 0.0254 + [(0.01415 - 0.0127)/2] \\ &= 0.0258 \text{ m} \end{aligned}$$

$h_b$  is the natural convection heat transfer coefficient of the fin like ends and was calculated by using Churchill-Chu [Ref. 22] correlation for natural convection for a smooth cylinder, as modified by Pulido [Ref.27].

$$h_b = \frac{k}{D_o} \left[ 0.6 + .387 \frac{\left[ \frac{g(\beta)(D_o^3)(\theta_b)(\tanh(nL_c))}{\nu(\alpha)(L_c)(n)} \right]^{1/6}}{\left[ 1 + \left[ \frac{.559}{Pr} \right]^{9/16} \right]^{8/27}} \right]^2$$

where

$$n = \left[ \frac{(h_b)(p)}{(k_{cu})(A_c)} \right]^{0.5}$$

Therefore an iterative technique was necessary to calculate  $h_b$ . The iterative technique used was to assume  $h_b$  was 190 W/m<sup>2</sup>K and continue the iteration until successive values are within 0.001 of each other. The fluid physical properties are calculated at the vapor mean film temperature, given by the following equation.

$$T_{film} = \frac{T_{sat_c} + \bar{T}_{wo}}{2}$$

$$T_{film} = \frac{2.28 + 9.98}{2}$$

$$T_{film} = 6.13^{\circ} C = 279.13^{\circ} K$$

For R-114, the physical properties are given in the program by:

Dynamic viscosity,  $T_{film}$  in  $^{\circ}K$

$$\mu = \exp[-4.4636 + (1011.47/T_{film})] \times 10^{-3}$$

$$\mu = 430.927 \times 10^{-6} \text{ kg/m s}$$

Specific heat,  $T_{film}$  in  $^{\circ}K$

$$C_p = [0.40188 + 1.65007 \times 10^{-3}(T_{film}) + 1.51494 \times 10^{-6}(T_{film}^2) - 6.67853 \times 10^{-10}(T_{film}^3)] \times 10^3$$

$$C_p = 966.31 \text{ J/kgK}$$

Density,  $T_{film}$  in  $^{\circ}K$

$$\rho = 16.0184533 (36.32 + 61.146414\psi^{1/3} + 17.476838\psi^{1/2} + 1.119828\psi^2)$$

where

$$\psi = 1 - \frac{[1.8(T_{film})]}{753.95}$$

and

$$\psi = .333$$

$$\rho = 1512.09 \frac{\text{kg}}{\text{m}^3}$$

Thermal conductivity of R-114,  $T_{film}$  in  $^{\circ}C$

$$k = 0.071 - (0.000261)(T_{film})$$



$$k = 6.936 \times 10^{-2} \text{ W/mK}$$

#### Prandtl Number

$$\text{Pr} = [(\text{Cp})\mu]/k$$

$$\text{Pr} = 6.003$$

#### Thermal Expansion Coefficient

$$\beta = - (1/\rho) (\Delta\rho/\Delta T)$$

$$\rho_{279.03} = 1512.395 \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{279.23} = 1511.824 \frac{\text{kg}}{\text{m}^3}$$

$$\beta = - (1/1512.395) [(.571)/(0.2)]$$

$$\beta = 1.89 \times 10^{-3} \text{ (1/K)}$$

#### Kinematic viscosity

$$\nu = \frac{\mu}{\rho}$$

$$\nu = \frac{430.927 \times 10^{-6}}{1512.09}$$

$$\nu = 2.849 \times 10^{-7} \text{ m}^2/\text{s}$$

#### Thermal Diffusivity

$$\alpha = \frac{k}{(\rho) C_p}$$

$$\alpha = \frac{6.936 \times 10^{-2}}{(1512.09) 966.31}$$

$$\alpha = 4.747 \times 10^{-8} \text{ m}^2/\text{s}$$

Knowing the above properties, the heat-transfer coefficient  $h_b$ , can be obtained by iteration

$$h_b = 362.57 \text{ W/m}^2\text{K}$$

Knowing this we can calculate  $n$

$$n = \left[ \frac{(h_b) (p)}{(k_{cu}) (A_c)} \right]^{0.5}$$

$$n = \left[ \frac{(362.57) (44.45 \times 10^{-3})}{(402.28) (3.0578 \times 10^{-6})} \right]^{0.5}$$

$$n = 36.19$$

then we can obtain  $q_f$

$$q_f = [(h_b) (p) (k_{cu}) (A_c)]^{0.5} (\theta_b) (\tanh[(n) (L_c)])$$

$$q_f = [(362.57) (.04445) (402.28) (3.0578 \times 10^{-5})]^{0.5} (7.70) (\tanh[(36.196) (0.0258)])$$

$$q_f = 2.51 \text{ W}$$

The corresponding results for the three inch section are

$$h_b = 289.47 \text{ W/m}^2\text{K}$$

$$q_f = 1.24 \text{ W}$$

Therefore, the heat transfer through the heated length of the tube is

$$q_s = q - q_f \text{ (1 inch section)} - q_f \text{ (3 inch section)}$$

$$q_s = (672.19 - 1.24 - 2.51) \text{ W}$$

$$q_s = 668.35 \text{ W}$$

and the heat flux and the heat transfer coefficient are as follows

$$q'' = q_s/A_s$$

$$= q_s/((\pi)(D_o)(L))$$

$$= (668.35)/((\pi)(0.01415)(.2032))$$

$$= 7.398 \times 10^4 \text{ W/m}^2$$

and finally the heat transfer coefficient

$$h = \frac{q_s}{A_s(T_{wo} - T_{sat})}$$

$$h = \frac{668.35}{9.033 \times 10^{-3}(7.70)}$$

$$h = 9.609 \times 10^3 \text{ W/m}^2\text{K}$$

## APPENDIX C: UNCERTAINTY ANALYSIS

The same data run (TBD1005) was chosen for the uncertainty analysis. Therefore, the measured and calculated parameters found in the sample calculation were used in this section. The uncertainty analysis performed was for a high heat flux, but the procedure could be performed at any heat flux to determine the uncertainty bands. All uncertainties are presented as a percentage of the calculated parameter. The uncertainty associated with the experimental parameters is calculated from the equation suggested by Kline and McClintock [Ref. 35]. For example:

$$R = R(x_1, x_2, \dots, x_n)$$

then

$$\delta R = \left[ \left( \frac{\partial R}{\partial x_1} \delta x_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} \delta x_2 \right)^2 + \dots + \left( \frac{\partial R}{\partial x_n} \delta x_n \right)^2 \right]^{0.5}$$

where

$\delta R$  = uncertainty of the desired dependant variable

$x_n$  = measured variables

$\delta x_n$  = uncertainty in measured variables

The boiling heat-transfer coefficient is given by

$$h = \frac{q_s}{A_s (T_{wo} - T_{sat})}$$

where

$$\bar{T}_{wo} = \bar{T}_{wi} - \frac{q [\ln(\frac{D_o}{D_{tc}})]}{2\pi (k_{cu}) (L)}$$

In the above equation, the second term on the right hand side is usually called the Fourier heat-transfer conduction term. If we define this as

$$\phi = \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

and

$$\theta_b = \bar{T}_{wo} - T_{sat_c}$$

With this notation, the uncertainty in the heat-transfer coefficient is obtained using the following equation.

$$\frac{\delta h}{h} = [(\frac{\delta q}{q})^2 + (\frac{\delta A_s}{A_s})^2 + (\frac{\delta \bar{T}_{wi}}{\theta_b})^2 + (\frac{\delta \phi}{\theta_b})^2 + (\frac{\delta T_{sat}}{\theta_b})^2]^{0.5}$$

where

$$q = V \times I$$

$$q = V(V) \times I(V) \times 60(V) \times 1(A/V)$$

and the uncertainty is

$$\frac{\delta q}{q} = [(\frac{\delta V}{V})^2 + (\frac{\delta I}{I})^2]^{0.5}$$

The accuracy in the voltage and current sensors are as follows

$$\delta V_{as} = \pm 0.05 \text{ V}$$

$$\delta A_{as} = \pm 0.025 \text{ A}$$

From the sample calculation section

$$V_{as} = 3.189 \text{ V}$$

$$A_{as} = 3.513 \text{ V}$$

Therefore,

$$\frac{\delta q}{q} = \left[ \left( \frac{\delta V_{as}}{V_{as}} \right)^2 + \left( \frac{\delta A_{as}}{A_{as}} \right)^2 \right]^{0.5}$$

$$\frac{\delta q}{q} = \left[ \left( \frac{0.05}{3.189} \right)^2 + \left( \frac{0.025}{3.513} \right)^2 \right]^{0.5}$$

$$\frac{\delta q}{q} = 1.72 \text{ percent}$$

Calculation of the uncertainty of the surface area is as follows

$$A_s = \pi(D_o)(L)$$

$$\frac{\delta A_s}{A_s} = \left[ \left( \frac{\delta D_o}{D_o} \right)^2 + \left( \frac{\delta L}{L} \right)^2 \right]^{0.5}$$

Knowing the dimensions of the tube from the manufacturer and estimated inaccuracies from work shop tools and human error, the uncertainty was calculated.

Dimensions

$$D_o = 14.15 \text{ mm}$$

$$L = 203.2 \text{ mm}$$

Inaccuracies in measurements

$$\delta D_o = 0.1 \text{ mm}$$

$$\delta L = 0.2 \text{ mm}$$

Uncertainty analysis performed

$$\frac{\delta A_s}{A_s} = [(\frac{\delta D_o}{D_o})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

$$\frac{\delta A_s}{A_s} = [(\frac{0.1}{14.15})^2 + (\frac{0.2}{203.2})^2]^{0.5}$$

$$\frac{\delta A_s}{A_s} = 0.7135 \text{ percent}$$

The uncertainty calculation for the Fourier conduction term given below

$$\frac{\delta \phi}{\phi} = [(\frac{\delta q}{q})^2 + (\frac{\delta k_{cu}}{k_{cu}})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

$k_{cu}$  was calculated using

$$k_{cu} = 434.0 - [0.112(\bar{T}_{wi})]$$

$$k_{cu} = 434.0 - [0.112(283.25)]$$

$$k_{cu} = 402.28 \text{ W/mK}$$

and its uncertainty

$$\delta k_{cu} = [(0.112(\delta \bar{T}_{wi}))^2]^{0.5}$$

$\delta T_{wi}$  and  $\delta T_{sat}$  are obtained using uncertainties in the thermocouple readings. Average wall inside temperature  $T_{wi}$  was obtained taking the average of six thermocouple readings inside the tube wall. The uncertainty associated with this variable is

$$\delta \bar{T}_{wi} = [6(\frac{\sum \delta T_{wi}}{6})^2]^{0.5}$$

where  $\delta T_{wi}$  for each thermocouple was obtained by taking the difference between the measured wall temperature and the average wall temperature. Using this method, it has been attempted to try and take into account some the uncertainty introduced by the fabrication procedure for the tube (ie. air gap). For this particular heat flux the following  $\delta T_{wi}$  were found for tube thermocouples 1, 2, 3, 4, 5, and 6.

$$\delta \bar{T}_{wi} = [(\frac{0.37}{6})^2 + (\frac{0.69}{6})^2 + (\frac{0.29}{6})^2 + (\frac{0.75}{6})^2 + (\frac{0.21}{6})^2 + (\frac{1.18}{6})^2]^{0.5}$$

$$\delta \bar{T}_{wi} = .274^\circ C$$

The uncertainty level for all remaining thermocouple readings (ie. excluding those in the tube wall which was considered to have a higher uncertainty) was estimated to be  $\pm 0.1^\circ C$  corresponding to an emf of approximately  $4 \mu V$ . Saturation temperature was obtained by taking the average of two thermocouple readings and the uncertainty in this temperature was calculated from the following equation.

$$\delta T_{sat} = [2(\frac{\delta T_c}{2})^2]^{0.5}$$

$$\delta T_{sat} = [2(\frac{0.1}{2})^2]^{0.5}$$

$$\delta T_{sat} = 0.07^\circ C$$

Knowing the uncertainty in the temperatures, we can now calculate the uncertainties in the following:



$$\delta k_{cu} = [(0.112(\delta \bar{T}_{wi}))^2]^{0.5}$$

$$\delta k_{cu} = [(0.112(283.25))^2]^{0.5}$$

$$\delta k_{cu} = 31.724 \text{ W/mK}$$

Now we can calculate the uncertainty in the Fourier conduction term

$$\frac{\delta \phi}{\phi} = [(\frac{\delta q}{q})^2 + (\frac{\delta k_{cu}}{k_{cu}})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

$$\frac{\delta \phi}{\phi} = [(0.0172)^2 + (\frac{31.724}{402.28})^2 + (\frac{0.2}{203.2})^2]^{0.5}$$

$$\frac{\delta \phi}{\phi} = 8.072 \text{ percent}$$

from the sample calculations we know that

$$\phi = 0.2679^\circ \text{ C} \quad \delta \phi = 0.2679(0.08072) = 0.0216^\circ \text{ C}$$

therefore:

$$\frac{\delta h}{h} = [(\frac{\delta q}{q})^2 + (\frac{\delta A_s}{A_s})^2 + (\frac{\delta \bar{T}_{wi}}{\theta_b})^2 + (\frac{\delta \phi}{\theta_b})^2 + (\frac{\delta Tsat}{\theta_b})^2]^{0.5}$$

$$\frac{\delta h}{h} = [(0.0172)^2 + (0.07135)^2 + (\frac{0.04}{7.70})^2 + (\frac{0.0216}{7.70})^2 + (\frac{0.07}{7.70})^2]^{0.5}$$

$$\frac{\delta h}{h} = 7.42 \text{ percent}$$

Finally the calculation of wall superheat temperature

$$\theta_b = \bar{T}_{wo} - Tsat$$

$$\frac{\delta \theta_b}{\theta_b} = [(\frac{\delta \bar{T}_{wo}}{\theta_b})^2 + (\frac{\delta Tsat}{\theta_b})^2]^{0.5}$$

$$\frac{\delta \theta_b}{\theta_b} = \left[ \left( \frac{0.274}{7.7} \right)^2 + \left( \frac{.07}{7.7} \right)^2 \right]^{0.5}$$

$$\frac{\delta \theta_b}{\theta_b} = 3.67 \text{ percent}$$

Table 4 shows the results of the uncertainty analysis performed. The high and low heat flux correspond to the approximate values of  $7.5 \times 10^4 \text{ W/m}^2$  and  $1 \times 10^3 \text{ W/m}^2$  respectively. Note that the highest uncertainty (over 50%) is in the wall superheat at very low heat flux ( $1 \text{ kW/m}^2$ ). This is due to the very low measured value of wall superheat ( $0.54 \text{ }^\circ\text{C}$ ) which can not be accurately measured. Thus higher uncertainty occurs at very low heat fluxes. However, once the wall superheat gets higher (at higher heat fluxes) the uncertainty in wall superheat decreases significantly (to about 4%) indicative of the fact that the measure wall temperature is relatively more accurate.

Table 4. UNCERTAINTY ANALYSIS RESULTS

VARIABLE	HIGH HEAT FLUX	LOW HEAT FLUX
$\theta_b$	7.7	0.54
$\bar{T}_{w1}$	10.25	2.80
$T_{sat}$	2.24	2.20
$\delta V_{as}/V_{as}$	1.57%	14.6%
$\delta A_{as}/A_{as}$	0.712%	7.9%
$\delta q/q$	1.72%	16.6%
$\delta D_o/D_o$	0.707%	0.707%
$\delta L/L$	0.098%	0.098%
$\delta A_s/A_s$	0.714%	0.714%
$\delta k_{cu}/k_{cu}$	7.89%	7.89%
$\delta \theta_b/\theta_b$	3.67%	52.37%
$\delta h/h$	7.42%	28.93%

## APPENDIX D: OPERATING PROCEDURE

### A. SYSTEM STARTUP

1. Power to the 28 kW (8 ton) refrigeration unit is provided by the breakers located in the main distribution panel located in the laboratory. These breakers were never secured. However, if power to this panel was lost, then these breakers must be reset.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position. This switch is always left on, unless unit was taken down for long repairs.

3. Push the start button in the control box for the recirculation pump. This control box is located on the bulkhead above the recirculation pump in the outside area adjacent to the refrigeration unit.

4. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately one hour to chill the sump to  $-15^{\circ}\text{C}$ . The thermometer in the ethylene glycol/water mixture (sump) must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

5. Energize the desired pumps by switching on the breakers in the main distribution power panel. Once the power is energized in the main power panel and after ensuring the pump suction valves are open, turn on the

pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol/water sump. The pumps are marked "auxiliary condenser" (Pump #2) and "instrumented tube condenser" (Pump #1), respectively in the breaker box. Flow in the auxiliary condensate coils can be controlled with the individual globe valves located at the coil penetrations on the apparatus. The auxiliary condenser coils will produce the fastest adjustments to the system pressure.

6. Energize the heater variac(s) desired by switching on the breakers (Bundle, and Simulation (for test 7 only)) in the main distribution power panel and individual breakers for each of these in the power distribution box (near apparatus).

7. After ensuring that the breakers for the heated tubes desired are in the "on" position, follow the experimental procedures for normal operation outlined in Chapter IV.

#### **B. SYSTEM SHUTDOWN**

1. Turn all variacs to the zero position and switch off all breakers in the power panels.

2. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on".

3. Allow the recirculation pump to operate for at least five minutes after switching off the refrigeration pump unit to dissipate any back pressure in the system.

4. Turn the breakers for the pumps to the off position at the switch boxes, and then secure the power at the main distribution power panel.

**C. EMERGENCY SHUTDOWN**

1. Secure all power at the main distribution power panel
2. Evacuate building
3. Call Fire Department

## APPENDIX E: PROGRAM DRP4RH

```

1000: FILE NAME: DRP4RH
1004: DATE: November 22, 1988
1008: REVISED: FEB 1992 (R. HAAS)
1012:
1016: BEEP
1020: PRINTER IS 1
1024: Idp=0
1028:
1032: PRINT USING "4X,""Select option default is 0: ""
1036: PRINT USING "6X,""0 Taking data or re-processing previous data""
1040: PRINT USING "6X,""1 Plotting data on Log-Log ""
1044: PRINT USING "6X,""2 Plotting data on Linear""
1048: PRINT USING "6X,""3 Purge""
1052: PRINT USING "6X,""4 Fixup""
1056: PRINT USING "6X,""5 Move""
1060: PRINT USING "6X,""6 Comb""
1064: PRINT USING "6X,""7 Read Plot""
1068:
1072: IDP IS A PROGRAM VARIABLE TO SELECT A SUBROUTINE
1076: INPUT Idp
1080: IF Idp=0 THEN CALL Main
1084: IF Idp=1 THEN CALL Plot
1088: IF Idp=2 THEN CALL Plin
1092: IF Idp=3 THEN CALL Purg
1096: IF Idp=4 THEN CALL Fixup
1100: IF Idp=5 THEN CALL Move
1104: IF Idp=6 THEN CALL Comb
1108: IF Idp=7 THEN CALL Readplot
1112: END
1116:
1120: SUB Main
1124: ICAL=THERMOCOUPLE CALIBRATION
1128: COM /C/ C(7)
1132: DIM Emf(35),T(35),Dia(6),D2a(6),Dia(6),Doe(6),La(6),Lue(6),Kcua(6),St(19),
Ldtc(20),Volt(2),Amp(11),Twa(5),Tw(5),Theta(5),Thetab(5),Q(5),Q1(5),Qdp(5)
1136: DIM Htube(5),Tn(5),Tp(6)
1140:
1144: THERMOCOUPLE ARRAY (C( )) INITIALIZATION
1148: DATA 0.10086091,25727.94369,-767345.9295,78025595.81
1152: DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1156: READ C(*)
1160:
1164: PRINT HEADER AND INITIALIZE TIME CLOCK
1168: PRINTER IS 701
1172: BEEP
1176: INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1180: OUTPUT DIRECTED TO DATA ACQUISITION SYSTEM (HP 3497A)
1184: OUTPUT 709:"TD":Date$
1188: OUTPUT 709:"TD"
1192: ENTER 709:Date$
1196: PRINT
1200: PRINT "          Month, date and time : ".Date$
1204: PRINT
1208: PRINT USING "10X,""NOTE: Program name DRP4RH""
1212: BEEP
1216:
1220: ON IS THE VARIABLE FOR DISC NUMBER FOR RECORD KEEPING ONLY
1224: INPUT "ENTER DISK NUMBER",On
1228: PRINT USING "16X,""Disk number = ",22".On

```

```

1232 BEEP
1236 Im=0
1240 INPUT "ENTER INPUT MODE (0=3497A,1=FILE, 0=DEFAULT)",Im
1244
1248 INPUT MODE ZERO IS FROM THE DATA ACQUISITION SYSTEM
1252 IF Im=0 THEN
1256 BEEP
1260 INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2files$
1264 PRINT USING "16X,""File name: "",14A";D2files$
1268
1272 CREATE BDAT FILE ON THE MASS STORAGE MEDIA
1276 CREATE BDAT D2files$,60
1280 CREATE AN INPUT/OUTPUT LINK TO OPEN FILES
1284 ASSIGN @File2 TO D2files$
1288
1292 CREATE DUMMY FILE UNTIL Nrun KNOWN
1296 Dfiles$="DUMMY"
1300 CREATE BDAT Dfiles$,60
1304 ASSIGN @File1 TO Dfiles$
1308 OUTPUT @File1;Dates$
1312
1316 CREATE A PLOT FILE
1320 BEEP
1324 INPUT "GIVE A NAME FOR THE PLOT FILE",Pfiles$
1328 CREATE BDAT Pfiles$,30
1332 ASSIGN @Plot TO Pfiles$
1336 BEEP
1340
1344 IDTC = NUMBER (TOTAL) OF DEFECTIVE THERMOCOUPLES
1348 INPUT "ENTER NUMBER OF DEFECTIVE TCS (0=DEFAULT)",Idtc
1352 LDTC = LOCATION OF DEFECTIVE THERMOCOUPLE
1356
1360 IF Idtc=0 THEN
1364 PRINT USING "16X,""No defective TCs exist""
1368 ELSE
1372 PRINT USING "16X,""Defective Thermocouples Indicated by -99.99""
1376 END IF
1380
1384 BEEP
1388 DEFECTIVE THERMOCOUPLES MAY BE IN CHANNELS 40-69
1392 THERMOCOUPLES ARE ENTERED AS DEFECTIVE BY COMPUTER CHANNEL NO.
1396 JDTC=COUNTER IN LOOP FOR DEFECTIVE THERMOCOUPLES
1400
1404 IF Idtc>0 THEN
1408 FOR Jdtc=0 TO Idtc-1
1412 INPUT "ENTER DEFECTIVE TC LOCATION (BY COMPUTER CHANNEL NUMBER)
",Ldtc(Jdtc)
1416 BEEP
1420 NEXT Jdtc
1424 END IF
1428 PRINTER IS 701
1432 OUTPUT @File1;Ldtc(*)
1436
1440 Im=1 option (THIS OPTION ALLOWS DATA ENTRY WITH DATA FILE)
1444 ELSE
1448 BEEP
1452 INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D2files$
1456 PRINT USING "16X,""File name: "",14A";D2files$
1460 ASSIGN @File2 TO D2files$
1464 ENTER @File2.Nrun

```



```

1468 ENTER @File2:Dold$,Ldct:*,Itt,Bop,Nht,Nato,Nrt,Corr
1470 BEEP
1476 INPUT "GIVE A NAME FOR PLOT FILE",Pfiles
1480 CREATE BCAT Pfiles,30
1484 ASSIGN @Plot TO Pfiles
1488 PRINT USING "16X,""This data set taken on   "",14A".Dold$
1492 BEEP
1496 PRINTER IS 1
1500 PRINT USING "4X,""SELECT TUBE TYPE""
1504 PRINT USING "6X,""0 SMOOTH""
1508 PRINT USING "6X,""1 FINNED(19/IN) ""
1512 PRINT USING "6X,""2 HIGH FLUX ""
1516 PRINT USING "6X,""3 TURBO-B ""
1520 INPUT Itt
1524 END IF
1528 IF Im=1 THEN GOTO 1768
1532 PRINTER IS 1
1536
1540 IF Im=0 THEN
1544 PRINT USING "4X,""Select tube type""
1548 PRINT USING "6X,"" 0 Smooth ""
1552 PRINT USING "6X,"" 1 FINNED 19/IN (DEFAULT)""
1556 PRINT USING "6X,"" 2 HIGH FLUX""
1560 PRINT USING "6X,"" 3 TURBO-B""
1564 PRINT USING "6X,"" 4 GROWTH""
1568 PRINT USING "6X,"" 5 GROWTH""
1572 PRINT USING "6X,"" 6 GROWTH""
1576 ITT=TUBE TYPE
1580 INPUT Itt
1584 OUTPUT @File1:Itt
1588 END IF
1592 PRINTER IS 701
1596 Itt=2
1600 PRINT USING "16X,""Tube Type:   "",DD":Itt
1604
1608 BEEP
1612 Bop=0
1616 INPUT "ENTER BULK OIL % (DEFAULT=0%) ",Bop
1620 OUTPUT @File1:Bop
1624 PRINT USING "16X,""Bulk oil%="",DD":Bop
1628
1632 BEEP
1633 Ipo=1
1634 INPUT "ENTER POOL HEIGHT ABOVE TOP TUBE (0=LESS THEN 5cm, 1=5cm OR GREATER
(DEFAULT)",Ipo
1635 OUTPUT @File1:Ipo
1636 PRINT USING "16X,""Pool height="",DD":Ipo
1637 BEEP
1639 NHT=NUMBER OF HEATED TUBES
1640 Nht=5
1644 INPUT "Enter number of heated instrumented tubes(default=5)",Nht
1648 OUTPUT @File1:Nht
1652 PRINT USING "16X,""Number of heated instrumented tubes="",DD":Nht
1653 BEEP
1655 Ipos=1
1656 IF Nht=1 THEN INPUT "WHICH POSITION IS THIS SINGLE TUBE (1 TO 5: DEF=1)",I
pos
1657 Ipos=Ipos-1
1658 BEEP
1660

```

```

1664 Natp=Number of active dummy pairs
1666 Natp=0
1672 INPUT "Enter number of active dummy pairs (Default=0)",Natp
1676 OUTPUT @File1:Natp
1680 PRINT USING "16X","Number of active dummy pairs=",DD":Natp
1684 BEEP
1686
1692 NRT=NUMBER OF ADDED HEATED TUBES TO ENHANCE BUNDLE EFFECT
1696 Nrt=0
1700 INPUT "Enter number of added heated tubes from simulation heaters(Default=
0)",Nrt
1704 OUTPUT @File1:Nrt
1708 PRINT USING "16X","Number of added heated tubes(from simulation heaters)="
",DD":Nrt
1712 BEEP
1716
1720 CORR IS CORRECTION FOR INSTRUMENTED TUBE HEIGHT
1724 Corr=0
1728 INPUT "WANT TO CORRECT TSAT FOR TUBE HEIGHT (0=YES(DEFAULT),1=NO)",Corr
1732 IF Corr=0 THEN PRINT USING "16X","TSAT is corrected instrumented heat
ed tube height""
1736 IF Corr=1 THEN PRINT USING "16X","TSAT is NOT corrected for instrumen
ted heated tube height""
1740 OUTPUT @File1:Corr
1744 BEEP
1748 ILQV=INPUT MODE: LIQUID, VAPOR,OR LIQUID VAPOR AVERAGE
1752 Ilqv=0
1756 INPUT "SELECT (0=LIQ(default),1=VAP,2=(LIQ+VAP)/2)",Ilqv
1760
1764 D1A=Diameter at thermocouple positions (meters)
1768 DATA .0122,0.0098,0.0105,0.0116,0.0,0
1772 READ Dia(*)
1776 D1=Dia(1)
1780
1784 D2=Diameter to base of fins (outside dia for smooth)(meters)
1788 DATA .0158,0.0125,0.0156,0.01415,0.0,0
1792 READ D2a(*)
1796 D2=D2a(1)
1800
1804 D1=Inside diameter of unenhanced ends (meters)
1808 DATA .0132,0.0109,0.0116,0.0127,0.0,0
1812 READ Dia(*)
1816 D1=Dia(1)
1820
1824 Do=Outside diameter of unenhanced ends (meters)
1828 DATA .015675,0.0125,0.015675,0.01415,0.0,0
1832 READ Doa(*)
1836 Do=Doa(1)
1840
1844 L=Length of enhanced surface (meters)
1848 DATA .2032,.2032,.2032,.2032,.2032,.2032
1852 READ La(*)
1856 L=La(1)
1860
1864 Lu=CORRECTED Length of unenhanced surface at the ends (METERS)
1868 LU=LFIN + THICKNESS/2
1872 DATA .0261,.0254,.0264,0.0258,0.0,0
1876 READ Lua(*)
1880 Lu=Lua(1)
1884

```

```

1688' Lc=connected length of 1 inch finned tile end
1692' DIM Lva(6)
1696' DATA .0765,.0762,.0773,.0765,.0.0.0
1900' READ Lva(*)
1904' Lv=Lva(1tt)
1908' Kcua=Thermal Conductivity of tube
1912' DATA 401,0.0.0.0.0.0
1916' READ Kcua(*)
1920' Kcu=Kcua(1tt)
1924' A=PI*(Dc^2-Di^2)/4
1928' F=PI*Do
1932' J=1
1936' Sx=0
1940' Sy=0
1944' Sxs=0
1948' Sxy=0
1952' Repeat:
1956'
1960' IF Im=0 THEN
1964'   Dtld=desired temperature of liquid
1968'   Dtld=47.5      'R-113
1969'   Dtld=2.2      'R-114
1972'   Ido=2
1976'   ON KEY 0,15 RECOVER 1952
1980'   PRINTER IS 1
1984'   PRINT USING "4X,""SELECT OPTION ""
1988'   PRINT USING "6X,""0=TAKE DATA""
1992'   PRINT USING "6X,""1=SET HEAT FLUX""
1996'   PRINT USING "6X,""2=SET Tset (DEFAULT SET FOR R-114)""
2000'   PRINT USING "4X,""NOTE: KEY 0 = ESCAPE""
2004'   Ido=desired option
2008'   BEEP
2012'   INPUT Ido
2016'
2020'   BEEP
2024'   Set default value for input
2028'   IF Ido>2 THEN Ido=2
2032'   Take data option
2036'   IF Ido=0 THEN 2440
2040'
2044' LOOP TO SET HEAT FLUX (FOR TOP INSTRUMENTED TUBE)
2048'   IF Ido=1 THEN
2052'     Qqdp=100000
2056'     PRINT USING "4X,""Qdp          QDPsim          Nrt          Qdpaux
2060'     Qtot""
2064'     PRINT USING "4X,""(W/m^2)          (W/m^2)          (W/m^2)
2068'     (W)""
2072'     Err=1
2076'     Reset,read channel 25-30,automatic scaling
2080'     Channel 25=aux amps,26=sim amps,27=inst volts,28=sim volts,29=aux
2084'     volts,30-34=inst amps
2088'     OUTPUT 709:"AR AF25 AL34 VRS"
2092'     FOR I=10 TO 11
2096'       OUTPUT 709:"AS SA"
2100'       ENTER 709:Amp(I)
2104'     NEXT I
2108'     FOR I=2 TO 2
2112'       OUTPUT 709:"AS SA"
2116'       ENTER 709:Volt(I)
2120'     NEXT I

```

```

2109      FOR I=0 TO 4
2112      OUTPUT 709:"AS SA"
2116      ENTER 709:Amp(I)
2117      NEXT I
2120      Calculate actual heat flux
2124      Q(0)=60*Volt(0)*Amp(Ipos)
2126      Qdp(0)=Q(0)/(PI*02*L)
2132      Qsim=60*20*Volt(1)*Amp(11)
2136      Qdpsim=Qsim/(PI*02*.2032*3)
2140      Qaux=60*20*Volt(2)*Amp(10)
2144      Qdpau=Qaux/(PI*.0160*.1778*4)
2146      Qtot=Q(0)+Nrt+Qsim+Qaux
2152      Nrt=Qdpsim/Qdp(0)
2156      IF ABS(Aqdp-Qdp)>Err THEN
2160          IF Aqdp>Qdp THEN
2164              BEEP 4000,.2
2168          ELSE
2172              BEEP 250,.2
2176          END IF
2180          IF Nrt<.1 THEN Nrt=0
2184          IF Qdpau<100 THEN Qdpau=0
2188          IF Qdpsim<100 THEN Qdpsim=0
2192          PRINT USING "4X,2(M2.3DE,2X),2X,(MOD,DD),2X,2(M2.3DE,2X)":Qdp
(0),Qdpsim,Nrt,Qdpau,Qtot
2196          WAIT 2
2200          GOTO 2076
2204      END IF
2208  END IF
2212
2216  LOOP TO SET Tset
2220  IF Ido=2 THEN
2224      IF Ikdt=1 THEN 2240
2228          BEEP
2232          INPUT "ENTER DESIRED Tset (DEFAULT=47.5 C - R-113)",Dtld
2233          INPUT "ENTER DESIRED Tset (DEFAULT=2.2 C - R-114)",Dtld
2236          Ikdt=1
2240          Oid1=0
2244          Oid2=0
2248          Nn=1
2252          Nns=Nn MOD 15
2256          Nn=Nn+1
2260          IF Nns=1 THEN
2264              PRINT USING "4X," DTset      Tld1      Tld2      Tibb
Tvat      Tvab      Tlev      ---
2268          END IF
2272          Read thermocouple voltages for vapor, liquid
2276          OUTPUT 705:"AF AF0 ALS VRS"
2280          Sample each thermocouple 20 times and report temp for each the
rmocouple, vapor=0,1,2; liquid=3&4
2284          FOR I=0 TO 5
2288              Sum=0
2292              OUTPUT 709:"AS SA"
2296              FOR J1=1 TO 20
2300                  ENTER 709:El1q
2304                  Sum=Sum+El1q
2308              NEXT J1
2312              Emf(I)=Sum/20
2316              T(I)=FNTvsv(Emf(I))
2320          NEXT I
2324          Compute average temperature of liquid

```

```

2338      Tlav=(T(0)+T(4))/2
2339      Compute average temperature of vapor
2340      Tlav1=(T(0)+T(1))/2
2341      Tlav2=T(2)
2342      Tlav=(T(0)+T(1)+T(2))/3
2343      IF ABS(Tlav-Dtld)>.1 THEN
2344          IF Tlav>Dtld THEN
2345              BEEP 4000,.2
2346          ELSE
2347              BEEP 250,.2
2348          END IF
2349      ELSE
2350          IF ABS(Tlav-Dtld)>.1 THEN
2351              IF Atld>Dtld THEN
2352                  BEEP 3000,.2
2353              ELSE
2354                  BEEP 800,.2
2355              END IF
2356          END IF
2357      END IF
2358      Err1=Tlav-Old1
2359      Old1=Tlav
2360      Err2=Tlav-Old2
2361      Old2=Tlav
2362      PRINT USING "4X,7(MODD.DD,3X)":Dtld,T(3),T(4),T(5),Tlav1,Tlav2,Tla
2363      v
2364      WAIT 2
2365      GOTO 2252
2366  END IF
2367
2368  TAKE DATA IF Im=0 LOOP
2369  IF Ikol=1 THEN 2452
2370      BEEP
2371      Ikol=1
2372      OUTPUT 709,"AR AF0 ALS VRS"
2373      FOR I=0 TO 5
2374          OUTPUT 709,"AS SA"
2375          Sum=0
2376          FOR J1=1 TO 20
2377              ENTER 709:E
2378              Sum=Sum+E
2379              IF I>2 THEN Et(J1-1)=E
2380          NEXT J1
2381          Kd1=0
2382          IF I>2 THEN
2383              Eave=Sum/20
2384              Sum=0
2385              FOR J1=0 TO 19
2386                  IF ABS(Et(J1)-Eave)<5.0E-6 THEN
2387                      Sum=Sum+Et(J1)
2388                  ELSE
2389                      Kd1=Kd1+1
2390                  END IF
2391              NEXT J1
2392              IF 1=0 THEN PRINT USING "4X,"Kd1 = ",DD",Kd1
2393              IF Kd1=10 THEN
2394                  BEEP
2395                  BEEP
2396                  PRINT USING "4X,"Too much scattering in data - re
2397                  peat data set""

```

```

2552             GOTO 1980
2556             END IF
2560             END IF
2564             Emf(I)=Sum*(20-Kd1)
2566         NEXT I
2572         OUTPUT 709:"AR AF40 AL69 VR5"
2576         FOR I=6 TO 35
2580             OUTPUT 709:"AS SA"
2584             Sum=0
2586             FOR J1=1 TO 5
2592                 ENTER 709:E
2596                 Sum=Sum+E
2600             NEXT J1
2604             Emf(I)=Sum/5
2608         NEXT I
2612
2616         READ VOLTAGES (27=Inst,28=Sim,29=Aux)
2620         OUTPUT 709:"AR AF27 AL25 VR5"
2624         FOR I=0 TO 2
2628             OUTPUT 709:"AS SA"
2632             ENTER 709:Volt(I)
2636         NEXT I
2640
2644         READ CURRENTS (30-34=Inst tubes,35-39=ACTIVE Dummy)
2648         OUTPUT 709:"AR AF30 AL39 VR5"
2652         FOR I=0 TO 9
2656             OUTPUT 709:"AS SA"
2660             ENTER 709:Amp(I)
2664         NEXT I
2668         Read Currents(25=Aux amps,26=Sim amps)
2672         OUTPUT 709:"AR AF25 AL26 VR5"
2676         FOR I=10 TO 11
2680             OUTPUT 709:"AS SA"
2684             ENTER 709:Amp(I)
2688         NEXT I
2692         ELSE
2696             ENTER @File2:Emf(*),Volt(*),Amp(*)
2700         END IF
2704
2708         CONVERT EMF'S TO TEMP,VOLT,CURRENT
2712         FOR I=0 TO 35
2716             T(I)=FNTvsv(Emf(I))
2720             IF I>5 AND Idtc>0 THEN
2724                 FOR I1=0 TO Idtc-1
2728                     IF Ldte(I1)=I-5+39 THEN T(I)=-99.99
2732                 NEXT I1
2736             END IF
2740         NEXT I
2744         Ntc=nr of thermocouples
2748         Ntc=6
2749         IF Ipos>0 THEN
2750             Q(Ipos)=50*Volt(0)*Amp(Ipos)
2751             Two(Ipos)=0
2752             Jj=0
2754             Ndtc=0
2755             FOR I=1 TO Ntc
2756                 Nn=Ipos+6+6+Jj
2757                 Jj=Jj+1
2759                 IF ABS(T(Nn))>99 THEN
2760                     T(Nn)=-99.99

```

```

2761         Ndtc=Ndtc+1
2762     ELSE
2763         Twa(Ipos)=Twa(Ipos)+T(Nn)
2764     END IF
2765     NEXT I
2766     Twa(Ipos)=Twa(Ipos)/(6-Ndtc)
2767     GOTO 2820
2768 END IF
2769 FOR I1=0 TO 4
2770     Q(I1)=60*Volt(0)*Amp(I1)
2771     Twa=Average temperature of the wall
2772     Twa(I1)=0
2773     Ndtc=0
2774     FOR I=1 TO Ntc
2775         Nn is counter in temp array, start at 6 (this is the first thermocouple in the tube bank)
2776         Nn=I+6+I+5
2777         IF ABS(T(Nn))>99 THEN
2778             T(Nn)=-99.99
2779             Ndtc=Ndtc+1
2780         ELSE
2781             Twa(I1)=Twa(I1)+T(Nn)
2782         END IF
2783     NEXT I
2784     Twa(I1)=Twa(I1)/(6-Ndtc)
2785 NEXT I1
2786 Tlav=(T(3)+T(4))/2
2787 Tvav=T(2)
2788 Tlav=(T(0)+T(1)+T(2))/3
2789 Tlav=T(5)
2790 Tcu=Twa(0)
2791 Kcu=FNKcu(Tcu) 'THERMAL CONDUCTIVITY OF COPPER
2792 'IF CURVE FIT NOT AVAIL USE ARRAY KCU(*)
2793 'FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
2794 FOR I=0 TO 4
2795     Tw(I)=Twa(I)-Q(I)*LOG(D2/D1)/(2*PI*Kcu*L)
2796     IF Ilqv=0 THEN Txs=Tlav
2797     IF Ilqv=1 THEN Txs=Tvav
2798     IF Ilqv=2 THEN Txs=(Tlav+T(2))*0.5
2799     IF Corr=1 THEN Thetab(I)=Tw(I)-Txs
2800     IF Corr=0 THEN Thetab(I)=Tw(I)-(Txs+.056+I*.129) 'R-114
2801     IF Corr=0 AND Ipo=1 THEN Thetab(I)=Tw(I)-(Txs+.054+I*.144) 'R-113
2802     IF Corr=0 AND Ipo=0 THEN Thetab(I)=Tw(I)-(Txs-1.078+I*.147+I) 'R-113
2803 NEXT I
2804
2805 COMPUTE VARIOUS PROPERTIES
2806 Tfilm=(Tw(0)+Txs)*.5 'FILM TEMPERATURE
2807 Rho=FNrho(Tfilm) 'DENSITY
2808 Mu=FNmu(Tfilm) 'VISCOSITY
2809 k=FNk(Tfilm) 'THERMAL CONDUCTIVITY
2810 Cp=FNcp(Tfilm) 'SPECIFIC HEAT
2811 Beta=FNbeta(Tfilm) 'THERMAL EXPANSION
2812 Ni=Mu/Rho 'KINEMATIC VISCOSITY
2813 Alpha=k/(Rho*Cp) 'THERMAL DIFFUSIVITY
2814 Pr=Ni/Alpha 'PRANDTL
2815
2816 COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT

```

```

2936 FOF UNENHANCED END(S)
2940 Lu=Lua/Itt)
2944 Hbar=190
2948 Fe=(Hbar*P/(kcu*A))**.5*Lu
2952 Tanh=FNtanh(Fe)
2956 Theta(Ipos)=Thetab(Ipos)*Tanh/Fe
2960 Xx=(9.81*Beta*Thetab/Ipos)*Qc**3*Tanh/(Fe*Ni*Alpha)**.1655E7
2964 Yy=(1+((.559/Pr)**(9/16))**(8/27))
2968 Hbarc=K/Do*(.6+.387*Xx/Yy)**2
2972 IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
2976 Hbar=(Hbar+Hbarc)*.5
2980 GOTC 2948
2984 END IF
2988
2992 COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S)
2996 Q1(0)=(Thetab(Ipos)*Tanh)*((Hbar*P*kcu*A)**.5)
3000 Qq=Q1(0)+Qq
3004 Z=Z+1
3008 IF Z=1 THEN
3012 Lu=Lv
3016 GOTC 2944
3020 END IF
3024 Z=0
3028 Q1pct=Qq/Q(Ipos)
3032 Qq=0
3036 As=PI*D2*L
3040 FOR I1=0 TO 4
3044 Q1(I1)=Q1pct*Q(I1)
3048 Qdp(I1)=(Q(I1)-Q1(I1))/As
3052 Htube(I1)=Qdp(I1)/Thetab(I1)
3056 NEXT I1
3060 PRINTER IS 701
3064
3068 RECORD TIME OF DATA TAKING
3072 IF Im=0 THEN
3076 OUTPUT 709:"TD"
3080 ENTER 709:Told$
3084 END IF
3088 CHURCHILL/CHU CORRELATION FOR NATURAL CONVECTION REGION
3092 Rae=9.81*Beta*Thetab(Ipos)*(D2)**3*Rho/(Mu*Alpha)
3096 Denom=(1+((.559/Pr)**(9/16))**(16/9))
3100 Nuch=(.6+.387*(Rae/Denom)**(1/5))**2
3104 Qch=K*Nuch*Thetab(Ipos)/(D2)
3108
3112 OUTPUT DATA TO PRINTER
3116 PRINTER IS 701
3120 PRINT
3124 PRINT USING "10X,""Data Set Number = ",DDD,2X,14A":J,Told$
3128 PRINT
3132 PRINT USING "10X,"" Tv1 Tv2 Tv3 T1d1 T1d2 T1d3
Tvav T1dav ""
3136 PRINT USING "10X,8(MDD.DD,2X)":T(0),T(1),T(2),T(3),T(4),T(5),Tvav,T1av
3140 PRINT
3144 PRINT USING "6X,""Tube Wall Temperatures (Deg C) Tnave Odp
H Thetab""
3148 PRINT USING "6X,"" 1 2 3 4 5 6 (Deg C) (W/m
2) (W/m**2.K) (K)""
3152 IF Ipos>0 THEN
3156 Jj=0
3160 FOR J1=0 TO 5

```



```

3133      Tp(Jj)=T(Ipos*E+Jj+6)
3134      Jj=Jj+1
3136      NEXT Jj
3137      Inn=Ipos+1
3138      PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)":Inn,Tp(0
,Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(Ipos),Qdp(Ipos),Htube(Ipos),Thetab(Ipos)
3139      GOTO 3177
3140      END IF
3141      Jj=0
3142      FOR Ij=0 TO Nht-1
3143          FOR Jj=0 TO 5
3144              Tp(Jj)=T(Ij*5+Jj+6)
3145              Jj=Jj+1
3146          NEXT Jj
3147          Jj=Ij+1
3148          FOR Jj=0 TO 4
3149              Tn(Jj)=1+Jj
3150          NEXT Jj
3151          PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)":Tn(Ij),T
p(0),Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(Ij),Qdp(Ij),Htube(Ij),Thetab(Ij)
3152      NEXT Ij
3153      PRINT
3154      PRINT USING "6X," Heat Flux and Tdel from Churchill/Chu Correlation i
s ",1(MZ.3DE),2X,1(MDD.DD)":Qch,Thetab(Ipos)
3155      PRINT
3156      Ok=1
3157      IF Im=0 THEN
3158          BEEP
3159          INPUT "OK TO STORE THIS DATA SET (1=Y(default),0=N)?",Ok
3160      END IF
3161      J=the counter for data sets
3162      IF Ok=1 OR Im=1 THEN J=J+1
3163      IF Ok=1 AND Im=0 THEN OUTPUT @File1:Emf(*),Volt(*),Amp(*)
3164      IF Im=1 OR Ok=1 THEN OUTPUT @Plot:Qdp(*),Htube(*),Thetab(*)
3165      Go_on=1
3166      IF Im=0 THEN
3167          BEEP
3168          INPUT "WILL THERE BE ANOTHER RUN (1=Y(default),0=N)?",Go_on
3169          Nrun=J
3170      IF Go_on=0 THEN 3272
3171      IF Go_on<>0 THEN Repeat
3172      ELSE
3173      IF J<Nrun+1 THEN Repeat
3174      END IF
3175      St=1
3176      BEEP
3177      INPUT "ARE YOU SURE YOUR READY TO TERMINATE (1=Y(DEFAULT),0=NO)?",St
3178      Go_on=1
3179      IF St>0 THEN 3280
3180      IF St=0 THEN GOTO 3240
3181      IF Im=0 THEN
3182          BEEP
3183          PRINT
3184          PRINT USING "10X,"NOTE: ",J," data runs were stored in file "
",10A",J-1,C2file$
3185      ASSIGN @File1 TO *
3186      OUTPUT @File2:Nrun-1
3187      ASSIGN @File1 TO D1file$
3188      ENTER @File1:Date$,Ldte(*),Itt,Bop,Nht,Natp,Nnt,Conn
3189      OUTPUT @File2:Date$,Ldte(*),Itt,Bop,Nht,Natp,Nnt,Conn

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```

3316         FOR I=1 TO Nrun-1
3320             ENTER @File1:Emf(*),Volt(*),Amp(*)
3324             OUTPUT @File2:Emf(*),Volt(*),Amp(*)
3328         NEXT I
3332         ASSIGN @File1 TO *
3336         PURGE "DUMMY"
3340     END IF
3344     BEEP
3348     PRINT
3352     PRINT USING "10X," "NOTE: ",Z2," X-Y pairs were stored in plot data f
ile ",10A":J-1,Pfile$
3356     ASSIGN @File2 TO *
3360     ASSIGN @Plot TO *
3364     BEEP
3368     SUBEND
3372
3376 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3380
3384 DEF FNKcu(Tcu)
3388 OFHC COPPER
3392 Tk=Tcu+273.15      !C TO K
3396 Kcu=434-.112*Tk      !250-300K USE FOR R-114 @2.2 C
3400 Kcu=433.0-.1*Tk      !200-400K USE FOR R-113 @47.5 C
3404 RETURN Kcu
3408 FNEND
3412
3416 DEF FNMu(T)
3420 CURVE FIT OF VISCOSITY
3424 Tk=T+273.15      !C TO K
3428 Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3 !R-114 170-360 K
3432 Mu=.0000134*(10^(503/(Tk-2.15))) !R113
3436 RETURN Mu
3440 FNEND
3444
3448 DEF FNCp(T)
3452 CURVE FIT OF Cp
3456 Tk=T+272.15      !C TO K
3460 Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3 !R-114 180-400 K
3464 Cp=(929+1.03*T)*.001 !R-113
3468 Cp=Cp*1000
3472 RETURN Cp
3476 FNEND
3480
3484 DEF FNRho(T)
3488 Tk=T+273.15      !C TO K
3492 X=1-(1.0*Tk/753.95) !K TO R
3496 Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^1.5+1.119828*X^2
3500 Ro=Ro/.062428      !R-114
3504 Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3) !R-113
3508 RETURN Ro
3512 FNEND
3516
3520 DEF FNPp(T) !GOOD FOR R-114/R-113
3524 Pp=FNCp(T)*FNMu(T)/FNRho(T)
3528 RETURN Pp
3532 FNEND
3536
3540 DEF FNK(T)
3544 Tk=360 K WITH T IN C
3548 K=.071-.000261*T

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```

3552 RETURN T
3556 FNEND
3560
3564 DEF FNTanh(Fe)
3568 P=EXP(Fe)
3572 Q=EXP(-Fe)
3576 Tanh=(P-Q)/(P+Q)
3580 RETURN Tanh
3584 FNEND
3588
3592 DEF FNTvsv(V)
3596 COM /Cc/ C(7)
3600 T=C(0)
3604 FOR I=1 TO 7
3608 T=T+C(I)*V^I
3612 NEXT I
3616 RETURN T
3620 FNEND
3624
3628 DEF FNBeta(T)
3632 Rop=FNRho(T+.1)
3636 Rom=FNRho(T-.1)
3640 Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
3644 RETURN Beta
3648 FNEND
3652 DEF FNPoly(X)
3656 COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
3660 X1=X
3664 Poly=B(0)
3668 FOR I=1 TO Nop
3672 IF Ilog=1 THEN X1=LOG(X)
3676 Poly=Poly+B(I)*X1^I
3680 NEXT I
3684 IF Ilog=1 THEN Poly=EXP(Poly)
3688 RETURN Poly
3692 FNEND
3696
3700'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3704
3708 SUE Poly(Dfile$(*),Np,Itn)
3712 DIM R(10),S(10),Sy(12),Sx(12),Xx(100),Yy(100),Xy(17)
3716 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
3720 COM /Xxyy/ Xp(5),Yp(5)
3724 FOR I=0 TO 4
3728 B(I)=0
3732 NEXT I
3736 In=1
3740 BEEP
3744 INPUT "ENTER DATA FILE NAME",Dfile$(0)
3746 BEEP
3752 INPUT "ENTER NUMBER OF X-Y PAIRS",Np
3756 BEEP
3760 INPUT "LIKE TO EXCLUDE DATA PAIRS (I=Y,0=N:DEFAULT)?",Ied
3764 IF Ied=1 THEN
3768 BEEP
3772 INPUT "ENTER NUMBER OF PAIRS TO BE EXCLUDED",Ipe
3776 END IF
3780 ASSIGN @File TO Dfile$(0)
3784 N=0
3788 BEEP

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3792 INPUT "ENTER THE ORDER OF POLYNOMIAL (DEFAULT=2) : ", N
3796 FOR I=0 TO N
3800   Sy(I)=0
3804   Sx(I)=0
3808 NEXT I
3812 IF led=1 AND lm=1 THEN
3816   FOR I=1 TO Ipe
3820     ENTER @File.Xy(*)
3824   NEXT I
3828 END IF
3832 FOR I=1 TO Np-Ipe
3836   ENTER @File.Xy(*)
3840   IF Opo=0 THEN
3844     Y=Xy(Itn-1)
3848     X=Xy(11+Itn)
3852   END IF
3856   IF Opo=1 THEN
3860     Y=Xy(5+Itn)
3864     X=Xy(11+Itn)
3868   END IF
3872   IF Opo=2 THEN
3876     Y=Xy(5+Itn)
3880     X=Xy(Itn-1)
3884   END IF
3888   IF Ilog=1 THEN
3892     X=LOG(X)
3896     Y=LOG(Y)
3900   END IF
3904   Xx(I)=X
3908   Yy(I)=Y
3912   R(I)=Y
3916   Sy(0)=Sy(0)+Y
3920   S(1)=X
3924   Sx(1)=Sx(1)+X
3928   FOR J=1 TO N
3932     R(J)=R(J-1)*X
3936     Sy(J)=Sy(J)+R(J)
3940   NEXT J
3944   FOR J=2 TO N*2
3948     S(J)=S(J-1)*X
3952     Sx(J)=Sx(J)+S(J)
3956   NEXT J
3960 NEXT I
3964 Sx(0)=Np
3968 FOR I=0 TO N
3972   C(I)=Sy(I)
3976   FOR J=0 TO N
3980     A(I,J)=Sx(I+J)
3984   NEXT J
3988 NEXT I
3992 FOR I=0 TO N-1
3996   CALL Divide(I)
4000   CALL Subtract(I+1)
4004 NEXT I
4008 B(N)=C(N)/A(N,N)
4012 FOR I=0 TO N-1
4016   B(N-1-I)=C(N-1-I)
4020   FOR J=0 TO I
4024     B(N-1-I)=B(N-1-I)-A(N-1-I,N-J)*B(N-J)
4028   NEXT J

```

```

4032     B(N-1-I)=B(N-1-I)+A(N-1-I,N-1-I)
4036 NEXT I
4040 IF Iprnt=0 THEN
4044     PRINT USING "12X,""EXPONENT    COEFFICIENT""
4048     FOR I=0 TO N
4052         PRINT USING "15X,DD,5X,MD.70E":I,B(I)
4056     NEXT I
4060     PRINT " "
4064     PRINT USING "12X,""DATA POINT    >          Y          Y(CALCULATED) DI
SCREPCANCY""
4068     FOR I=1 TO Nd
4072         Yc=B(0)
4076         FOR J=1 TO N
4080             Yc=Yc+B(J)*Xx(I)^J
4084         NEXT J
4088         D=Yy(I)-Yc
4092         PRINT USING "15X,3D,4X,4(MD.5DE,1X)":I,Xx(I),Yy(I),Yc,D
4096     NEXT I
4100 END IF
4104 ASSIGN @File TO *
4108 SUBEND
4112!
4116 SUB Divide(M)
4120 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,0po,Ilog
4124 FOR I=M TO N
4128     Ao=A(I,M)
4132     FOR J=M TO N
4136         A(I,J)=A(I,J)/Ao
4140     NEXT J
4144     C(I)=C(I)/Ao
4148 NEXT I
4152 SUBEND
4156!
4160 SUB Subtract(K)
4164 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,0po,Ilog
4168 FOR I=K TO N
4172     FOR J=K-1 TO N
4176         A(I,J)=A(K-1,J)-A(I,J)
4180     NEXT J
4184     C(I)=C(K-1)-C(I)
4188 NEXT I
4192 SUBEND
4196!
4200 SUB Plin
4204 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,0po,Ilog
4208 COM /Xyyy/ Xx(5),Yy(5)
4212 PRINTER IS 705
4216 BEEP
4220 INPUT "SELECT (0=h/h0% same tube,1=h(HF)/h(sm))",Irt
4224 BEEP
4228 INPUT "WHICH Tset (1=6.7,0=-2.2)",Isat
4232 Xmin=0
4236 Xmax=10
4240 Xstep=2
4244 IF Irt=0 THEN
4248     Ymin=0
4252     Ymax=1.4
4256     Ystep=.2
4260 ELSE
4264     Ymin=0

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4265     Yma=-15
4272     Ystep=5
4276 END IF
4280 BEEP
4284 PRINT "IN:SP1,IF 2300,2200,6300,6800."
4288 PRINT "SC 0,100,0,100,TL 2,0."
4292 Sfx=100/(Xmax-Xmin)
4296 Sfy=100/(Ymax-Ymin)
4300 PRINT "PU 0,0 PD"
4304 FOR Xa=Xmin TO Xmax STEP Xstep
4308     X=(Xa-Xmin)*Sfx
4312     PRINT "PA",X,"",0: XT:"
4316 NEXT Xa
4320 PRINT "PA 100,0:PU:"
4324 PRINT "PU PA 0,0 PD"
4328 FOR Ya=Ymin TO Ymax STEP Ystep
4332     Y=(Ya-Ymin)*Sfy
4336     PRINT "PA 0,"",Y,"YT"
4340 NEXT Ya
4344 PRINT "PA 0,100 TL 0 2"
4348 FOR Xa=Xmin TO Xmax STEP Xstep
4352     X=(Xa-Xmin)*Sfx
4356     PRINT "PA":X,"",100: XT"
4360 NEXT Xa
4364 PRINT "PA 100,100 PU PA 100,0 PD"
4368 FOR Ya=Ymin TO Ymax STEP Ystep
4372     Y=(Ya-Ymin)*Sfy
4376     PRINT "PD PA 100,"",Y,"YT"
4380 NEXT Ya
4384 PRINT "PA 100,100 PU"
4388 PRINT "PA 0,-2 SR 1.5,2"
4392 FOR Xa=Xmin TO Xmax STEP Xstep
4396     X=(Xa-Xmin)*Sfx
4400     PRINT "PA":X,"",0:"
4404     PRINT "CP -2,-1.LB":Xa:""
4408 NEXT Xa
4412 PRINT "PU PA 0,0"
4416 FOR Ya=Ymin TO Ymax STEP Ystep
4420     IF ABS(Ya)<1.E-5 THEN Ya=0
4424     Y=(Ya-Ymin)*Sfy
4428     PRINT "PA 0,"",Y,""
4432     PRINT "CP -4,-.25.LB":Ya:""
4436 NEXT Ya
4440 Xlabel$="Oil Percent"
4444 IF Irt=0 THEN
4448     Ylabel$="h/h0%"
4452 ELSE
4456     Ylabel$="h/hsmooth"
4460 END IF
4464 PRINT "SF 1.5,2:PU PA 50,-10 CP":-LEN(Xlabel$)/2,"0.LB":Xlabel$,""
4468 PRINT "PA -11.50 CP 0,"":-LEN(Ylabel$)/2+5/6,"DI 0,1.LB":Ylabel$,""
4472 PRINT "CP 0,0"
4476 Ipn=0
4480 BEEP
4484 INPUT "WANT TO PLOT DATA FROM A FILE (1=N,0=N)?",Oip
4488 Icn=0
4492 IF Oip=1 THEN
4496 BEEP
4500 INPUT "ENTER THE NAME OF THE DATA FILE",L_files
4504 BEEP

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```

4502 INPUT "SELECT (0=LINEAR, 1=LOG(X,Y))",Ilog
4512 ASSIGN @File TO @_files
4516 BEEP
4522 INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4524 BEEP
4526 INPUT "ENTER THE NUMBER OF Y-Y PAIRS STORED",Npairs
4532 BEEP
4536 INPUT "ENTER DESIRED HEAT FLUX",Q
4540 BEEP
4544 PRINTER IS 1
4546 PRINT USING "4X,""Select a symbol ""
4552 PRINT USING "4X,""1 Star 2 Plus sign""
4556 PRINT USING "4X,""3 Circle 4 Square""
4560 PRINT USING "4X,""5 Rombus""
4564 PRINT USING "4X,""6 Right-side-up triangle""
4568 PRINT USING "4X,""7 Up-side-down triangle""
4572 INPUT Sym
4576 PRINTER IS 705
4580 PRINT "PU DI"
4584 IF Sym=1 THEN PRINT "SM+"
4588 IF Sym=2 THEN PRINT "SM+"
4592 IF Sym=3 THEN PRINT "SMo"
4596 Nn=4
4600 IF Ilog=1 THEN Nn=1
4604 IF Md>1 THEN
4608     FOR I=1 TO (Md-1)
4612         ENTER @File:Xa,Ya
4616     NEXT I
4620 END IF
4624 Q1=Q
4628 IF Ilog=1 THEN Q=LOG(Q)
4632 FOR I=1 TO Npairs
4636     ENTER @File:Xa,B(0)
4640     Ya=B(0)
4644     FOR K=1 TO Nn
4648         Ya=Ya+B(K)*Q^K
4652     NEXT K
4656     IF Ilog=1 THEN Ya=EXP(Ya)
4660     IF Ilog=0 THEN Ya=Q1/Ya
4664     IF Int=0 THEN
4668         IF Xa=0 THEN
4672             Yo=Ya
4676             Ya=1
4680             ELSE
4684                 Ya=Ya/Yo
4688             END IF
4692     ELSE
4696         Hsm=FNHsmooth(C,Xa,Isat)
4700         Ya=Ya/Hsm
4704     END IF
4708     Xx(I-1)=Xa
4712     Yy(I-1)=Ya
4716     X=(Xa-Xmin)*Sfx
4720     Y=(Ya-Ymin)*Sfy
4724     IF Sym=2 THEN PRINT "SM"
4728     IF Sym=4 THEN PRINT "SF 1.4,2.4"
4732     PRINT "PA",X,Y,""
4736     IF Sym=3 THEN PRINT "SF 1.2,1.6"
4740     IF Sym=4 THEN PRINT "UCD,4.99,0,-6,-4,0,0,6,4,0,1"
4744     IF Sym=5 THEN PRINT "UCB,0.99,-2,-6,-3,6,3,6,3,-6,1"

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4748 IF Sym=E THEN PRINT "UCC,S.3.99,3,-8,-6.0,3,6:"
4752 IF Sym=T THEN PRINT "UCC,-S.3.99,-3,6,6,0,-3,-6:"
4756 NEXT I
4760 BEEP
4764 ASSIGN @File TO *
4768 END IF
4772 PRINT "PU SM"
4776 BEEP
4780 INPUT "WANT TO PLOT A POLYNOMIAL (I=Y,0=N)?",Oip
4784 IF Oip=1 THEN
4788 BEEP
4792 INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
4796 Iprnt=1
4800 CALL Poly(Itn)
4804 FOR Xa=Xmin TO XmaX STEP Xstep/25
4808 Icn=Icn+1
4812 Ya=FNPoly(Xa)
4816 Y=(Ya-Ymin)*Sfy
4820 X=(Xa-Xmin)*Sfx
4824 IF Y<0 THEN Y=0
4828 IF Y>100 THEN GOTO 4868
4832 Pu=0
4836 IF Ipn=1 THEN Idf=Icn MOD 2
4840 IF Ipn=2 THEN Idf=Icn MOD 4
4844 IF Ipn=3 THEN Idf=Icn MOD 8
4848 IF Ipn=4 THEN Idf=Icn MOD 16
4852 IF Ipn=5 THEN Idf=Icn MOD 32
4856 IF Idf=1 THEN Pu=1
4860 IF Pu=0 THEN PRINT "PA",X,Y,"PD"
4864 IF Pu=1 THEN PRINT "PA",X,Y,"PU"
4868 NEXT Xa
4872 PRINT "PU"
4876 Ipn=Ipn+1
4880 GOTO 4480
4884 END IF
4888 BEEP
4892 INPUT "WANT TO QUIT (I=Y,0=N)?",Iquit
4896 IF Iquit=1 THEN 4904
4900 GOTO 4480
4904 PRINT "PU SP0"
4908 SUBEND
4912 SUB Stats
4916 PRINTER IS 701
4920 J=0
4924 K=0
4928 BEEP
4932 INPUT "PLOT FILE TO ANALYZE?",Files
4936 ASSIGN @File TO Files
4940 BEEP
4944 INPUT "LAST RUN No?(0=QUIT)",Nn
4948 IF Nn=0 THEN 5092
4952 Nn=Nn-J
4956 Sx=0
4960 Sy=0
4964 Sz=0
4968 Sxs=0
4972 Sys=0
4976 Szs=0
4980 FOR I=1 TO Nn
4984 J=J+1

```



```

4998 ENTEF @File.C,T
4999 H=Q/T
4999 Sx=Sx+Q
5000 Sxs=Sxs+Q^2
5004 Sy=Sy+T
5008 Sys=Sys+T^2
5012 Sz=Sz+H
5016 Szs=Szs+H^2
5020 NEXT I
5024 Qave=Sx/Nn
5028 Tave=Sy/Nn
5032 Have=Sz/Nn
5036 Sdevq=SQR(ABS((Nn*Sxs-Sx^2)/(Nn*(Nn-1))))
5040 Sdevt=SQR(ABS((Nn*Sys-Sy^2)/(Nn*(Nn-1))))
5044 Sdevh=SQR(ABS((Nn*Szs-Sz^2)/(Nn*(Nn-1))))
5048 Sh=100*Sdevh/Have
5052 Sq=100*Sdevq/Qave
5056 St=100*Sdevt/Tave
5060 IF K=1 THEN 5084
5064 PRINT
5068 PRINT USING "11X,""DATA FILE:"",14A":File$
5072 PRINT
5076 PRINT USING "11X,""RUN Htube      SdevH      Qdp      SdevQ      Thetab SdevT""
5080 K=1
5084 PRINT USING "11X,DD,2(2X,D.3DE,1X,3D.2D),2X,DD.3D,1X,3D.2D":J,Have,Sh,Qave
,Sq,Tave,St
5088 GOTO 4940
5092 ASSIGN @File1 TO *
5096 PRINTER IS 1
5100 SUBEND
5104 SUB Coef
5108 COM /Cply/ A(10,10),C(10),B(4),N,lpnt,Opp,Ilog
5112 BEEP
5116 INPUT "GIVE A NAME FOR CROSS-PLOT FILE",Cpf$
5120 BEEP
5124 INPUT "OUTPUT TYPE (0=q vs Dt, 1=h vs Dt, 2=h vs q)",Opp
5128 CREATE BDAT Cpf$,6
5132 ASSIGN @File TO Cpf$
5136 BEEP
5140 INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
5144 BEEP
5148 INPUT "ENTER OIL PERCENT (-1=STOP)",Bop
5152 BEEP
5156 INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5160 IF Bop<0 THEN 5176
5164 CALL Poly(Itn)
5168 OUTPUT @File,Bop,B*
5172 GOTO 5144
5176 ASSIGN @File TO *
5180 SUBEND
5184
5188'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5192'
5196 SUB Plot
5200 COM /Cply/ A(10,10),C(10),B(4),Nop,lpnt,Opp,Ilog
5204 DIM xy(17)
5208 INTEGER I1
5212 PRINTER IS 1
5216 BEEP

```

```

5220 Idv=1
5224 INPUT "LIKE DEFAULT VALUES FOR PLOT (1=Y(DEFAULT),0=N)",Idv
5228 Opo=0
5232 BEEP
5236 PRINT USING "4X,";"Select Option: ""
5240 PRINT USING "6X,";"0 q versus delta-T(DEFAULT)""
5244 PRINT USING "6X,";"1 h versus delta-T""
5248 PRINT USING "6X,";"2 h versus q""
5252 INPUT Opo
5256 BEEP
5260 INPUT "SELECT UNITS (0=SI(DEFAULT),1=ENGLISH)",Iun
5264 PRINTER IS 705
5268 IF Idv<>1 THEN
5272 BEEP
5276 INPUT "ENTER NUMBER OF CYCLES FOR X-AXIS",Cx
5280 BEEP
5284 INPUT "ENTER NUMBER OF CYCLES FOR Y-AXIS",Cy
5288 BEEP
5292 INPUT "ENTER MIN X-VALUE (MULTIPLE OF 10)",Xmin
5296 BEEP
5300 INPUT "ENTER MIN Y-VALUE (MULTIPLE OF 10)",Ymin
5304 ELSE
5308 IF Opo=0 THEN
5312 Cy=2
5316 Cx=2
5320 Xmin=1
5324 Ymin=1000
5328 END IF
5332 IF Opo=1 THEN
5336 Cy=2
5340 Cx=2
5344 Xmin=1
5348 Ymin=100
5352 END IF
5356 IF Opo=2 THEN
5360 Cy=2
5364 Cx=2
5368 Xmin=1000
5372 Ymin=100
5376 END IF
5380 END IF
5384 BEEP
5388 PRINT "IN:SP1:IP 2300,2200,6300,6800:"
5392 PRINT "SC 0,100,0,100:TL 2,0:"
5396 Sf=100/Cx
5400 Sf=100/Cy
5404 BEEP
5408 INPUT "WANT TO BY-PASS CAGE (1=Y, 0=NO(DEFAULT))",Ibp
5412 IF Ibp=1 THEN 5906
5416 PRINT "PU 0,0 PD"
5420 Nn=9
5424 FOR I=1 TO Cx+1
5428 Xat=Xmin*10**(I-1)
5432 IF I=Cx+1 THEN Nn=1
5436 FOR J=1 TO Nn
5440 IF J=1 THEN PRINT "TL 2 0"
5444 IF J=2 THEN PRINT "TL 1 0"
5448 Xa=Xat*J
5452 X=LST/Xa/Xmin*Sf
5456 PRINT "PA",X,"C",Xat

```

```

5460     NEXT J
5464 NEXT I
5466 PRINT "PA 100,0,PU:"
5470 PRINT "PU PA 0,0 PD"
5476 Nn=9
5480 FOR I=1 TO Cy+1
5484     Yat=Ymin*10^(I-1)
5488     IF I=Cy+1 THEN Nn=1
5492     FOR J=1 TO Nn
5496         IF J=1 THEN PRINT "TL 2 0"
5500         IF J=2 THEN PRINT "TL 1 0"
5504         Ya=Yat*J
5508         Y=LGT(Ya/Ymin)*Sfy
5512         PRINT "PA 0,":Y,"YT"
5516     NEXT J
5520 NEXT I
5524 PRINT "PA 0,100 TL 0 2"
5528 Nn=9
5532 FOR I=1 TO Cx+1
5536     Xat=Xmin*10^(I-1)
5540     IF I=Cx+1 THEN Nn=1
5544     FOR J=1 TO Nn
5548         IF J=1 THEN PRINT "TL 0 2"
5552         IF J>1 THEN PRINT "TL 0 1"
5556         Xa=Xat*J
5560         X=LGT(Xa/Xmin)*Sfx
5564         PRINT "PA":X,".100: XT"
5568     NEXT J
5572 NEXT I
5576 PRINT "PA 100,100 PU PA 100,0 PD"
5580 Nn=9
5584 FOR I=1 TO Cy+1
5588     Yat=Ymin*10^(I-1)
5592     IF I=Cy+1 THEN Nn=1
5596     FOR J=1 TO Nn
5600         IF J=1 THEN PRINT "TL 0 2"
5604         IF J>1 THEN PRINT "TL 0 1"
5608         Ya=Yat*J
5612         Y=LGT(Ya/Ymin)*Sfy
5616         PRINT "PD PA 100,":Y,"YT"
5620     NEXT J
5624 NEXT I
5628 PRINT "PA 100,100 PU"
5632 PRINT "PA 0,-2 SR 1.5,2"
5636 I1=LGT(Xmin)
5640 FOR I=1 TO Cx+1
5644     Xa=Xmin*10^(I-1)
5648     X=LGT(Xa/Xmin)*Sfx
5652     PRINT "PA":X,".0."
5656     IF I1>0 THEN PRINT "CP -2,-2,LB10:PF -2,2,LB":I1:""
5660     IF I1<0 THEN PRINT "CP -2,-2,LB10:PR 0,2,LB":I1:""
5664     I1=I1+1
5668 NEXT I
5672 PRINT "PU PA 0,0"
5676 I1=LGT(Ymin)
5680 Y10=10
5684 FOR I=1 TO Cy+1
5688     Ya=Ymin*10^(I-1)
5692     Y=LGT(Ya/Ymin)*Sfy
5696     PRINT "PA 0,":Y,""

```

```

S700      PRINT "CP -4,-.25:LB10:PR -2.2:LB".I1;"
S704      I1=I1+1
S708      NEXT I
S712      BEEP
S716      Id1=1
S720      INPUT "WANT USE DEFAULT LABELS (1=Y(DEFAULT),0=N)?",Id1
S724      IF Id1<>1 THEN
S726          BEEP
S732          INPUT "ENTER X-LABEL",Xlabel$
S736          BEEP
S740          INPUT "ENTER Y-LABEL",Ylabel$
S744      END IF
S746      IF Opo<2 THEN
S752          PRINT "SR 1,2:PU PA 40,-14:"
S756          PRINT "LB(T:PR -1.5,3 PD PR 1.2,0 PU:PR .5,-4:LBwo:PR .5,1:"
S760          PRINT "LE-T:PR .5,-1:LBsat:PR .5,1:"
S764          IF Iun=0 THEN
S768              PRINT "LB) / (K)"
S772          ELSE
S776              PRINT "LB) / (F)"
S780          END IF
S784      END IF
S788      IF Opo=2 THEN
S792          IF Iun=0 THEN
S796              PRINT "SR 1.5,2:PU PA 40,-14:LBq / (W/m:SR 1,1.5:PR 0.5,1:LB2:SR 1
.5,2:PR 0.5,-1:LB)"
S800          ELSE
S804              PRINT "SR 1.5,2:PU PA 34,-14:LBq / (Btu/hr:PR .5,.5:LB.:PR .5,-.5:
.5,.5:"
S808              PRINT "LBft:PR .5,1:SR 1,1.5:LB2:SR 1.5,2:PR .5,-1:LB):"
S812          END IF
S816      END IF
S820      IF Opo=0 THEN
S824          IF Iun=0 THEN
S828              PRINT "SR 1.5,2:PU PA -12,40:DI 0,1:LBq / (W/m:PR -1,0.5:SR 1,1.5:L
B2:SR 1.5,2:PR 1,.5:LB)"
S832          ELSE
S836              PRINT "SR 1.5,2:PU PA -12,32:DI 0,1:LBq / (Btu/hr:PR -.5,.5:LB.:PR
.5,.5:"
S840              PRINT "LBft:SR 1,1.5:PR -1,.5:LB2:PR 1,.5:SR 1.5,2:LB)"
S844          END IF
S848      END IF
S852      IF Opo>0 THEN
S856          IF Iun=0 THEN
S860              PRINT "SR 1.5,2:PU PA -12,38:DI 0,1:LBh / (W/m:PR -1,.5:SR 1,1.5:LB
2:SR 1.5,2:PR .5,.5:"
S864              PRINT "LB.:PR .5,0:LBK)"
S868          ELSE
S872              PRINT "SR 1.5,2:PU PA -12,28:DI 0,1:LBh / (Btu/hr:PR -.5,.5:LB.:PR
.5,.5:"
S876              PRINT "LBft:PR -1,.5:SR 1,1.5:LB2:SR 1.5,2:PR .5,.5:LB.:PR .5,.5:
LBF)"
S880          END IF
S884      END IF
S888      IF Id1=0 THEN
S892          PRINT "SF 1.5,2:PU PA 50,-16 CP",-LEN(Xlabel$)/2,"0:LE":Xlabel$;"
S896          PRINT "PA -14,50 CP 0",-LEN(Ylabel$)/2,"5/6:DI 0,1:LB":Ylabel$;"
S900          PRINT "CP 0,0 CI"
S904      END IF
S908      Ipn=0

```

```

5910 Repeat:
5916 x11=1.E+6
5920 xul=-1.E+6
5924 lcn=0
5926 BEEP
5930 O=1
5936 INPUT "WANT TO PLOT DATA FROM A FILE (1=Y(DEFAULT),0=N)?",O
5940 IF O=1 THEN
5944 BEEP
5948 INPUT "ENTER THE NAME OF THE DATA FILE",Dfiles(0)
5952 ASSIGN @File TO Dfiles(0)
5956 BEEP
5960 Npairs=20
5964 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED(DEFAULT=20)",Npairs
5968 BEEP
5972 Itn=Itn+1
5976 INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5980 BEEP
5984 PRINTER IS 1
5988 INPUT "WANT DEFAULT SYMBOLS? (YES=0 (DEFAULT),NO=1)",Symb
5992 Sym=Itn+2
5996 IF Symb=0 THEN
6000 GOTO 6036
6004 END IF
6008 PRINT USING "4X,""Select a symbol:""
6012 PRINT USING "6X,""1 Star 2 Plus sign""
6016 PRINT USING "6X,""3 Circle 4 Square""
6020 PRINT USING "6X,""5 Rombus""
6024 PRINT USING "6X,""6 Right-side-up triangle""
6028 PRINT USING "6X,""7 Up-side-down triangle""
6032 INPUT Sym
6036 PRINTER IS 705
6040 PRINT "PU DI"
6044 IF Sym=1 THEN PRINT "SM+"
6048 IF Sym=2 THEN PRINT "SM+"
6052 IF Sym=3 THEN PRINT "SMo"
6056 FOR I=1 TO Npairs
6060 ENTER @File:Xy(+)
6064 IF Opo=0 THEN
6068 Ya=Xy(Itn-1)
6072 Xa=Xy(11+Itn)
6076 END IF
6080 IF Opo=1 THEN
6084 Ya=Xy(5+Itn)
6088 Xa=Xy(11+Itn)
6092 END IF
6096 IF Opo=2 THEN
6100 Ya=Xy(5+Itn)
6104 Xa=Xy(Itn-1)
6108 END IF
6112 IF Xa<X11 THEN X11=Xa
6116 IF Xa>Xul THEN Xul=Xa
6120 IF lcn=1 THEN
6124 IF Opo=2 THEN Xa=Xa*.1E
6128 IF Opo=0 THEN Ya=Ya*.1761
6132 IF Opo=0 THEN Ya=Ya*.317
6136 IF Opo=2 THEN Xa=Xa*.317
6140 END IF
6144 Y=LGIT(Xa/Xmin)*Sfx
6148 Y=LGIT(Ya/Ymin)*Sfy

```

```

6152 KJ=0
6156 CALL Symb(X,Y,Sym,Icl,KJ)
6160 GOTO 6212
6164 IF Sym>3 THEN PRINT "SM"
6168 IF Sym<4 THEN PRINT "SR 1.4,2.4"
6172 IF Icl=0 THEN
6176 PRINT "PA",X,Y,""
6180 ELSE
6184 PRINT "PA",X,Y,"PD"
6188 END IF
6192 IF Sym>3 THEN PRINT "SR 1.2,1.6"
6196 IF Sym=4 THEN PRINT "UC2,4.99,0,-8,-4,0,0.8,4,0:"
6200 IF Sym=5 THEN PRINT "UC3,0.99,-3,-6,-3,6,3,6,3,-6:"
6204 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-6,-6,0,3,8:"
6208 IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8:"
6212 NEXT I
6216 PRINT "PU"
6220 BEEP
6224 Ilab=1
6228 INPUT "WANT TO LABEL? (1=Y(DEFAULT),0=N)",Ilab
6232 IF Ilab=1 THEN
6236 PRINT "SP0:SP2"
6240 BEEP
6244 IF Klab=0 THEN
6248 Xlab=65
6252 Ylab=85
6256 INPUT "ENTER INITIAL X,Y LOCATIONS",Xlab,Ylab
6260 Xtt=Xlab-5
6264 Ytt=Ylab+8
6268 PRINT "SR 1,1.5"
6272 PRINT "SM:PA",Xtt,Ytt,"LB Tube % File"
6276 Ytt=Ytt-3
6280 PRINT "PA",Xtt,Ytt,"LB No Oil Name"
6284 IF Sym=1 THEN PRINT "SM+"
6288 IF Sym=2 THEN PRINT "SM+"
6292 IF Sym=3 THEN PRINT "SMo"
6296 Klab=1
6300 END IF
6304 KJ=1
6308 CALL Symb(Xlab,Ylab,Sym,Icl,KJ)
6312 PRINT "SR 1,1.5:SM"
6316 IF Sym<4 THEN PRINT "PR 2,0"
6320 PRINT "PR 2,0:LB".Iti:"
6324 BEEP
6328 INPUT "ENTER BOP(0=DEFAULT)",Bop
6332 IF Bop<10 THEN PRINT "PR 3,0:LB":Bop:""
6336 IF Bop>9 THEN PRINT "PR 1.5,0:LB":Bop:""
6340 PRINT "PR 2,0:LB":Dfiles(0):""
6344 PRINT "SP0:SP1:SR 1.5,2"
6348 Ylab=Ylab-5
6352 END IF
6356 BEEP
6360 ASSIGN @File TO *
6364 X11=X11/1.2
6368 Xul=Xul*1.2
6372 GOTO 8040
6376 END IF
6380 PRINT "PU SM"
6384 BEEP
6388 6c_on=1

```

```

6392 INPUT "WANT TO PLOT A POLYNOMIAL (1=Y(DEFAULT),0=N)?",Gc_on
6396 IF Gc_on=1 THEN
6400 BEEP
6404 PRINTER IS 1
6408 INPUT "WANT DEFAULT LINE TYPE? (YES=0 (DEFAULT),NO=1)",Ln
6412 Ipn=1tn
6416 IF Ln=0 THEN
6420 GOTO 6448
6424 END IF
6428 PRINT USING "4X,""Select line type:""
6432 PRINT USING "6X,""0 Solid line""
6436 PRINT USING "6X,""1 Dashed""
6440 PRINT USING "6X,""2,,,5 Longer line - dash""
6444 INPUT Ipn
6448 PRINTER IS 705
6452 BEEP
6456 Ilog=1
6460 INPUT "SELECT (0=LIN,1=LOG(DEFAULT))",Ilog
6464 Iprnt=1
6468 CALL Poly(Dfile$(*),Npairs,Itn)
6472 FOR Xx=0 TO Cx STEP Cx/200
6476 Xa=Xmin+10*Xx
6480 IF Xa<X11 OR Xa>Xul THEN 6572
6484 Icn=Icn+1
6488 Pu=0
6492 IF Ipn=1 THEN Idf=Icn MOD 2
6496 IF Ipn=2 THEN Idf=Icn MOD 4
6500 IF Ipn=3 THEN Idf=Icn MOD 8
6504 IF Ipn=4 THEN Idf=Icn MOD 16
6508 IF Ipn=5 THEN Idf=Icn MOD 28
6512 IF Idf=1 THEN Pu=1
6516 Ya=FNPoly(Xa)
6520 IF Ya<Ymin THEN 6572
6524 IF Iun=1 THEN
6528 IF Opo<2 THEN Xa=Xa+1.8
6532 IF Opo>0 THEN Ya=Ya+.1761
6536 IF Opo=0 THEN Ya=Ya+.317
6540 IF Opo=2 THEN Xa=Xa+.317
6544 END IF
6548 Y=L6T(Ya/Ymin)*Sfy
6552 X=L6T(Xa/Xmin)*Sfx
6556 IF Y<0 THEN Y=0
6560 IF Y>100 THEN GOTO 6572
6564 IF Pu=0 THEN PRINT "PA",X,Y,"PD"
6568 IF Pu=1 THEN PRINT "PA",X,Y,"PU"
6572 NEXT Xx
6576 PRINT "PU"
6580 END IF
6584 BEEP
6588 INPUT "WANT TO QUIT (1=Y,0=N(DEFAULT))",Iqt
6592 IF Iqt=1 THEN 6600
6596 GOTO 5916
6600 PRINT "PU PA 0,0 SP0"
6604 SUBEND
6606
6612 !XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6616
6620 SUB Symb(X,Y,Sym,Icl,Fj)
6624 IF Sym>3 THEN PRINT "SM"
6628 IF Sym<4 THEN PRINT "SF 1.4,2.4"

```

```

6632 Yed=0
6636 IF Yj=1 THEN Yed=.6
6640 IF Ic1=0 THEN
6644 PRINT "PA",X,Y+Yed,""
6648 ELSE
6652 PRINT "PA",X,Y+Yed,"PD"
6656 END IF
6660 IF Sym=3 THEN PRINT "SF 1.2,1.6"
6664 IF Sym=4 THEN PRINT "UC2,4.99,0,-6,-4,0,0,8,4,0:"
6668 IF Sym=5 THEN PRINT "UC3,0.99,-3,-6,-3,6,3,6,3,-6:"
6672 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8:"
6676 IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8:"
6680 IF Kj=1 THEN PRINT "SM:PR 0,-.8"
6684 SUBEND
6688
6692'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6696
6700 SUE Fixup
6704' FILE: FIXUP
6708
6712 DIM Emf(34),Amp(11),Volt(4),Ldte(4)
6716 BEEP
6720 INPUT "OLD FILE TO FIXUP",D2files$
6724 ASSIGN @File2 TO D2files$
6728 D1files$="TEST"
6732 CREATE BDAT D1files$,60
6736 ASSIGN @File1 TO D1files$
6740 ENTER @File2:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Conn
6744 OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Conn
6748 FOR I=1 TO Nrun
6752 ENTER @File2:Told$,Emf(*),Volt(*),Amp(*)
6756 IF I=1 THEN 6764
6760 OUTPUT @File1:Bop,Told$,Emf(*),Volt(*),Amp(*)
6764 NEXT I
6768 ASSIGN @File2 TO *
6772 ASSIGN @File1 TO *
6776' RENAME "TEST" TO D2_files$
6780 BEEP 2000,.2
6784 BEEP 4000,.2
6788 BEEP 4000,.2
6792 SUBEND
6796
6800'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6804
6808 SUE Move
6812' FILE NAME: MOVE
6816
6820 DIM A(66),B(66),C(66),D(66),E(66),F(66),G(66),H(66),J(66),K(66),L(66),M(66)
6824 DIM N(66),Emf(34),Volt(2),Amp(11),Ldte(4)
6828 BEEP
6832 INPUT "OLD FILE TO MOVE",D2_files$
6836 ASSIGN @File2 TO D2_files$
6840 ENTER @File2:Nrun,Told$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Conn
6844 FOR I=1 TO Nrun
6848 ENTER @File2:Told$
6852 ENTER @File2:A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M(
1),N(I)
6856 ENTER @File2:Emf(*),Volt(*),Amp(*)
6860 NEXT I

```



```

6864 ASSIGN @File2 TO *
6866 BEEP
6872 INPUT "SHIFT DISK AND HIT CONTINUE",O1
6876 BEEP
6880 INPUT "INPUT BDAT SIZE",Size
6884 CREATE BDAT D2_files,Size
6888 ASSIGN @File1 TO D2_files
6892 OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
6896 FOR I=1 TO Nrun
6900     OUTPUT @File1:Told$
6904     OUTPUT @File1:A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M
(I),N(I)
6908     OUTPUT @File1:Emf(*),Volt(*),Amp(*)
6912 NEXT I
6916 ASSIGN @File1 TO *
6920 RENAME "TEST" TO D2_files
6924 BEEP 2000,.2
6928 BEEP 4000,.2
6932 BEEP 4000,.2
6936 PRINT "DATA FILE MOVED"
6940 SUBEND
6944!
6948!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6952!
6956 SUB Purg
6960 BEEP
6964 INPUT "ENTER FILE NAME TO BE DELETED",File$
6968 PURGE File$
6972 GOTO 6960
6976 SUBEND
6980!
6984!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6988!
6992 SUB Comb
6996! FILE NAME: COMB
7000!
7004 DIM Emf(34),Volt(2),Amp(11),Ldte(4)
7008 BEEP
7012 INPUT "OLD FILE TO FIXUP",D2_files
7016 ASSIGN @File2 TO D2_files
7020 D1_files="TEST"
7024 CREATE BDAT D1_files,30
7028 ASSIGN @File1 TO D1_files
7032 ENTER @File2:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
7036 IF K=0 THEN OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
7040 FOR I=1 TO Nrun
7044 ENTER @File2:Bop,Told$,Emf(*),Volt(*),Amp(*)
7048 OUTPUT @File1:Bop,Told$,Emf(*),Volt(*),Amp(*)
7052 NEXT I
7056 ASSIGN @File2 TO *
7060 RENAME "TEST" TO D2_files
7064 BEEP 4000,.2
7068 BEEP
7072 O1a=1
7076 INPUT "WANT TO ADD ANOTHER FILE (1=Y,0=N(default))?",O1a
7080 IF O1a=1 THEN
7084 K=1
7088 BEEP
7092 INPUT "GIVE NEW FILE NAME",Nfiles
7096 ASSIGN @File2 TO Nfiles

```

```

7100 GOTO 7032
7104 END IF
7108 ASSIGN @File2 TO *
7112 SUBEND
7116
7120 'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
7124
7128 SUB Readplot
7132 DIM Qdp(5),Htube(5),Thetab(5)
7136 PRINTER IS 701
7140 INPUT "ENTER FILE NAME",Files
7144 INPUT "ENTER THE NUMBER OF DATA PAIRS",Nrun
7148 ASSIGN @File1 TO Files
7152 FOR I=1 TO Nrun
7156     ENTER @File1:Qdp(*),Htube(*),Thetab(*)
7160     PRINT Qdp(*)
7164     PRINT
7166     PRINT Htube(*)
7172     PRINT
7176     PRINT Thetab(*)
7180     PRINT
7184     PRINT
7188 NEXT I
7192 SUBEND

```

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